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Industry 4.0 in a project context: Introducing 3D printing in construction projects

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ABSTRACT

As an example of Industry 4.0 in a project context, 3D printing of concrete has the potential to provide a paradigm shift for construction processes with significant implications for project management. This study investigates and reports the enablers and barriers of implementing the innovative 3D printing technology in construction projects, based on a literature review and case study interviews in construction companies. 3D printing can make construction processes more effective, provided that project managers can utilize the potential. The interviews with industry representatives highlighted the issue of cost efficiency of the technology. There is a need to show practical project examples on cost efficiency of the 3D printing technology. To those who manage new technologies 3D printing and other aspects of Industry 4.0 represent an opportunity, while those who struggle to work with and understand new technologies, they represent a challenge or even a threat. Future project managers better be in the first category.

1. Introduction

Industry 4.0, sometimes referred to as The Fourth Industrial Revolution (Buehler et al., 2018), builds upon the established digitalization but includes a synthesis of technologies (Schwab, 2015), transforming entire systems of production, management and governance. Currently, emerging technologies include materials science, quantum computing, artificial intelligence (AI), Internet of Things (IoT), autonomous vehicles, robotics and 3D printing (Schwab, 2017). 3D printing and other manifestations of Industry 4.0 can change the way projects are managed. Porter and Heppelmann explain how Industry 4.0 means that connected products will dramatically change the way firms work (Porter-Heppelmann, 2014). This process is ongoing, and can be expected to influence project-based business. Vieira and Romero-Torres (VieiraRomero-Torres, 2016) point out that additive manufacturing such as 3D printing can change project management practices with examples from the aerospace industry. While a central decision-making approach typically is employed in traditional project management, experiences from manufacturing indicate that a decentralized project management approach can be adopted when Industry 4.0 principles are used in projects (Cakmakci et al., 2019; Hofmann and Rüsch, 2017). This affects both communication in projects, as well as the used technologies. Implementing such technologies are projects in themselves, that needs to be managed, and new managerial styles such as the ones used in innovation and new product development seems appropriate (Pajares-Poza et al., 2017). In addition, the new technologies will affect how construction projects are managed. Olsson (2006) has pointed out that project managers tend to be conservative and avoid flexibility in the execution phase of projects. Project managers tend to focus on execution, with a determined management style (Olsson, 2008; Ramos et al., 2016).

Previous studies have identified a number of barriers to innovation in the construction sector (Besklubova et al., 2021). A general conservative attitude in the sector is frequently mentioned in studies (Olsson et al., 2019), to the extent that industry professionals sometimes get annoyed. We have therefore chosen to focus on commercial issues, which are understood as key barriers to innovation, such as high initial innovation costs, the perceived lack of risk funding, and long pay-back time for

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investments.

Different aspects of digitalization and pressure on improved productivity and an increased focus on sustainability are key drivers that generate the need for new competencies in the construction industry. There are also a number of barriers that need to be bridged to appropriately address these trends. To begin with there are a number of unique characteristics of the construction industry (Vrijhoef and Koskela, 2005) such as the one-of-a-kindness of the project, price-oriented tendering, the temporary organization and varied production sites. In addition, there are distributed and fragmented value chains (Diekmann et al., 2004; Mossman, 2009; Sarhan and Fox, 2013) which means that there frequently is poor communication and coordination system in the project and a heavy reliance on workers with diversified skills and background.

3D printing and hybrid additive/subtractive manufacturing is one of several technologies that offer opportunities for the construction industry and offers a new tool for project managers. A key advantage is that 3D printing can offer increased flexibility in the construction process. To be able to utilize the advantages of the technology, it is important to be aware of industry characteristics. Research interest in 3D printing for construction has increased significantly in recent years (Besklubova et al., 2021) and there is a need to investigate and discuss barriers, drivers, enablers, and impacts for construction project innovation (Ghaben and Jaaron, 2017). As a contribution to such research, this study investigates and reports drivers, enablers and barriers of implementing the innovative 3D printing technology in construction and project management, based on a literature review and interviews from a case study with three construction companies. In accordance to Ghaben and Jaaron (2017), we discuss drivers as factors that create the need for organisations to innovate, enablers as factors that facilitate innovation and finally barriers as factors that impede the uptake of innovation. In a wider project management context, the study uses 3D-printing as a case to study innovation in a project-based industry and in particular innovation inspired by the ongoing development of Industry 4.0.

2. On innovation and industrialization in construction

The construction industry faces technological changes evolving from Industry 4.0 which will change the way of doing projects, driven by technologies such as prefabrication, BIM, automated and robotic equipment, wireless sensors and 3D printing (Buehler et al., 2018). Because the construction industry is project-based, the number of stakeholders is large. All parts of the value chain need to be informed of the consequences of new innovative products (World Economic Forum, 2016). Architects, engineers, clients, contractors, subcontractors, and suppliers need to cooperate in this area. This is important strategically as well as on a project basis. Not to forget the governmental role that facilitates politics and procurement processes for innovation, for instance, industry-wide standards and certifications. Risk-sharing between stakeholders in the industry is important (World Economic Forum, 2016).This challenges the role of project managers and other champions of change, and raises issues such as; who has to follow up risks, make sure that agreements are in place about risk-sharing and ensure that the risks taken do not have negative consequences for stakeholders involved, but also to open up for the opportunities that emerge (Johansen et al., 2019).

As a project-based industry, the construction industry is facing the two-fold challenge of meeting increasing demand with limited resources. Due to pressures such as population growth, climate change, urbanisation, and increasing demands for social development, the identification of the most efficient solutions is becoming more challenging. Innovation in construction projects is key for project success (Engström and Stehn, 2016). Olsson et al. (2019) point out that the construction industry has evolved from craftsmanship towards an industrialized business, thanks to the development and implementation of technological and organizational innovations. However, there are indications that some innovations have not been utilized to their full potential in the construction industry. Several studies document that the construction industry has adopted innovations to a lesser extent than comparable industries (World Economic Forum, 2016) and reports by Latham (1994) and Egan (1998) are unfortunately still relevant. Terms such as “adversarial”, “ineffective”, “fragmented” and suggestions that the industry is “incapable of delivering for its clients”, are supported in more recent analyses (World Economic Forum, 2016; KPMG, 2016).

Innovation is a fashionable and iridescent concept (HauschildtSalomo et al., 2016). During the last decades, there have been ground-breaking innovations in means of increasing the use of technology and industrialization of products and processes. Nevertheless, the construction industry still underperforms when it comes to both quality of its products and productivity (World Economic Forum, 2016). Resistance to innovation is a main challenge to the industry. However, there are several examples of a willingness to exploit the potential of new technologies in construction context. This paper studies one such emerging technology for construction; that of additive manufacturing technologies and in particular 3D printing of concrete.

2.1. 3D printing in relation to industrialization of construction projects

Technological development of the construction and building sector incorporates innovation within both processes and products. Industrialization of the construction process denotes the development of processes. However, the development of the process can be the result of innovation in products. Industrialization of the building and construction process is therefore a generic term covering a range of methods and approaches with the joint goal of increasing the efficiency and productivity of the building and construction sector (CIB, 2010; Atkin, 2014; Ågren and Wing, 2014).

Traditionally, industrialization revolves around attaining higher degrees of standardization of materials and processes. It allows for specialization of steps or components in the production, allowing it to be split among several actors. Companies may invest in specialized equipment to handle capital-intensive and highly specialized aspects of the production, allowing others to focus capital and knowledge in other areas. In construction and building industrialization has traditionally resulted in approaches based on a higher degree of pre-fabrication and offsite production moving the value-adding activities upstream in the supply chain (Barlow et al., 2003; Pan et al., 2007; Thuesen and Hvam, 2011). Industry 4.0, automation and Internet of Things (IoT) can contribute to reversing this trend, moving value-adding activities back to the building site. Richard (2005) define industrialization as the *“aggregation of a large market to divide into fractions the investment in strategies and technologies capable, in return, of simplifying the production and therefore reducing the costs”* and goes on to describe the stages of industrialization as *“prefabrication”, “mechanization”, “automation”, “robotics” and “reproduction”*.

Construction projects can have different degrees of “projectification”. Gibb (2001) distinguishes between four categories of construction as follows: (1) Traditional “one-of-a-kind” construction utilizes component manufacture and sub-assembly in which raw materials and components are brought to the site where the value-adding actions are carried out. (2) Non-volumetric pre-assembly describes when two-dimensional elements are prefabricated and assembled on-site (walls, floors, etc.). (3) With volumetric pre-assembly volumes of specific parts of the building are produced off-site and assembled onsite within an independent frame. (4) Finally, modular building describes construction where most of the production is carried out off-site leaving only assembly and finishing operations to take place on-site. By applying this view on industrialization, Jonsson and Rudberg (2014) developed a framework illustrating different degrees of off-site production based on a manufacturing framework by Miltenburg (2005). The original framework presented a manufacturing strategy based on the number of products and the production volumes ranging from the "job shop" (unique products) to mass production (Continuous flow). Similarly, they present a linking of construction approach or strategy as a function of standardization, volumes and volume of off-site production.

3D printing is introducing changes to this traditional vision of industrialization of the construction process by simultaneously allowing for transferring value-adding activities back to the construction site and moving only the production of complex components off-site. While Miltenburg's framework incorporates both output and process-oriented strategies (Just-in-time and flexible manufacturing systems), the adapted version leaves the process perspective relatively untouched. The application of process-oriented strategies, such as lean construction in construction projects is independent of the degree of off-site production, yet they represent in our view, industrialization of the construction process. Process-focused innovation in building and construction has been ongoing for a long time. Gann (1996) pointed to supply chain management and product development as areas where providers of industrialized housing concepts could learn from car manufacturers. Lean construction has formalized this line of thinking by adapting lean thinking (Womack and Jones, 2010) and Toyota production systems (Ohno, 1988) to a construction setting (Howell, 1999; Ballard and Howell, 2003; Höök and Stehn, 2008). It is interesting to study how industrialization and the introduction of new technologies will impact project management. On one hand, standardisation, off-site production and technologies such as 3D printing can enable greater control for project managers and thus reduce complexity. On the other hand, new technologies introduce new uncertainties, especially before the technologies are mature. This study is intended to give a contribution in gaining knowledge about such issues.

2.2. Barriers to the introduction of innovative technologies in construction

The construction sector is traditionally seen as a business with little innovation, typically lower than other industries such as manufacturing or energy infrastructure. However, the adoption of innovative construction technologies is so relevant, as it can have a disruptive effect on this industry, opening it to new paradigms. Several studies have shown that construction has failed to adopt innovation to improve its performance as in other industries (World Economic Forum, 2016).

Lack of a formal process to transfer knowledge from one project to another project is one of the biggest challenges found in the literature for innovation implementation (Ekambaram et al., 2010; Maghsoudi et al., 2016). Feedback is important to improve processes, products and services. Feedback is needed from users, customers, regulators and other stakeholders. For innovation initiators, feedback is very important to make it successful at the user end. One of the features of construction projects is uniqueness. Almost every contraction project is unique in some dimension. If there is no formal knowledge transfer system from one project to another project, the chances of failure for innovation increase.

Construction projects have faced both internal and external barriers for the efficient adaption of innovations that have been introduced. Internal barriers mainly stem from the traditional and conservative construction culture that have long prioritized the cost-efficient and on-time delivery of the project to the customer with a little focus for improvements both within and between the projects. External barriers are mainly originated from the dispersed and fragmented nature of the construction value chains that involve multiple stakeholders and contractors, making it highly challenging for successful implementation of innovations holistically. Based on the literature study, Table 1 summarizes the barriers that are encountered by the construction industry, regarding all innovation types within product, process, and service categories.

Table 1
Barriers of innovation in construction industry *identified in literature.*

Barriers of innovation	Reference
Focus on cost efficiency and lack of funding in R&D	(World Economic Forum, 2016), (Hardie et al., 2005)
Lack of formal process following and knowledge transfer from one project to another project.	(World Economic Forum, 2016), (Davis et al., 2016; Walker and Walker, 2016)
Multiple stakeholders lack in cooperation to implement innovation	(World Economic Forum, 2016), (Davis et al., 2016), (Barlow, 2000)
Conservative behaviour of small companies regarding innovation	World Economic Forum (2016)
Lack of young talent due to job insecurity (Construction projects are temporary jobs)	World Economic Forum (2016)
Loose coupling between stakeholders	Dubois and Gadde (2002)
Non-profitability	Choi et al. (2011)
Lack of coordination between market needs and innovation	Nam and Tatum (1997)
Locked system created by construction products	Nam and Tatum (1988)
Innovation missing in the main strategy of the companies	Barlow (2000)
Focus on success and failure of the project (Creates lack of attention on implementation of the innovation)	Maghsoudi et al. (2016)
Lack of skilled workforce in the market for innovation implementation.	(Ozorhon et al., 2013) (Davis et al., 2016)
Conservative behaviour of suppliers	Ozorhon et al. (2013)
Lack of the management of innovation in construction organisations	Xue et al. (2014b)
Construction industry fragmentation	Davis et al. (2016)
Conservatism in construction industry	KPMG (2016)
Risk in adopting new technology	KPMG (2016)
High cost of the innovation	KPMG (2016)
Lack of positive environment for innovation in organisations	Dulaimi et al. (2005)

2.3. Enablers for the introduction of innovative technologies in construction

The literature search mentioned in the methods section has also identified several enablers as countermeasures to overcome barriers and succeed in the implementation of innovations. The enablers are summarized in Table 2.

Table 2
Enablers of innovation in construction industry *identified in literature.*

Enablers of innovation	Reference
Mega projects are ideal for innovation development and implementation	(Worsnop et al., 2016) (Brockmann et al., 2016)
Effective leadership	(Ozorhon et al., 2013) (Dulaimi et al., 2005)
Stakeholders coordination	Ozorhon et al. (2013)
Market demand (External environmental factors or pressure)	(Davis et al., 2016; Xue et al., 2014b) (KPMG, 2016)
Effective flow of information from project to project	(Xue et al., 2014b) (Hardie et al., 2005)
Integrated design	Xue et al. (2014b)
Technology capacity of organisations	(Davis et al., 2016) (KPMG, 2016)
Organization strategies for innovation adoption	(Davis et al., 2016) (Dulaimi et al., 2005)
Efficiency in cost reduction and planning	KPMG (2016)
Growth	KPMG (2016)
Profitability	KPMG (2016)
Increasing governmental regulations	KPMG (2016)
providing a reward for creativity in organisations,	Dulaimi et al. (2005)
Increasing risk-taking behaviour,	Dulaimi et al. (2005)
Industry-academia collaboration	Hardie et al. (2005)
Recruitment for fresh graduates	Hardie et al. (2005)

3. Methodology

In this study, a comprehensive literature review was conducted first and the literature was analysed qualitatively to identify the drivers and barriers to the application of industrialized building and construction, in general and for 3D printing in particular. The review was done using a range of databases and keywords, to ensure that important publications were not overlooked. Keywords included; Innovation, Construction, 3D-printing; Additive; Characteristics; Challenges. The main searches were done using Google scholar.

Based on the literature review, an interview-guide was developed and applied in a series of semi-structured interviews. This qualitative method is used to gather data withindividual variation, to verify outcomes, and to clarify discrepancies between the actual intervention and how participants experience it (Sandelowski, 1996). It also has the advantage of including stakeholders in the research dialogue and enables them to become active participants in an inquiry (Denzin et al., 2008). Interview techniques can follow three main directions. There is the non-directive interview technique where the interviewee leads the process and decides where the conversation will go, and the directive interview where specific questions are asked that follow a predefined theme proposed by the researcher (Hammersley and Atkinson, 2007). In semi-structured interviews the questions are also prepared, but a more open conversational style allows follow-up questions to be included (Skinner, 2012). In this case semi-structured interviews were conducted with five informants from three different construction companies. The informants are anonymous. The interviews took place using skype technology and lasted approximately 1 h each. The feedback and requirements of the informant are in focus in the data presented, rather than the specifications found in the interview guide. The differing backgrounds and professions of the informants meant they placed emphasis on a variety of issues during the interviews and this is exemplified in the analysis.

Companies were selected from a range of European countries and positions within the construction industry in order to extrapolate and improve the generalizability of the results. The three companies are known here as, Company A, Company B, and Company C for confidentiality. The participants had a variety of roles and experience with 3D printing. We did not require them to be experts in 3D printing but were interested in their point of view and experiences based on their own roles and experiences, as well as the company's. These companies are larger actors either within Scandinavia or the EU and there was an expectation that they could be using or planning to use 3D printing technology.

Company A is a large international construction company with headquarters in Scandinavia and 60000 employees worldwide. Three informants came from Company A, two from a Nordic facility, and one from an EU facility. One of the Nordic participants works as a director in business management with 41 years of experience in leadership, project development and management. The other Nordic informant from Company A is the Head of the Technique Department and responsible for 50 consultants in several departments. The informant from the EU facility is the director of Innovation and Business Improvement at his country's branch of the company. Company B is a global civil engineering company with headquarters in the EU and 50000 employees worldwide. The informant from Company B has twenty years of experience in the company and worked as a site manager for seven years. He has been responsible for Research and design (R&D) since 2011 in the European region of the corporation. Company C is a Nordic architecture firm with 450 employees in Scandinavia. The informant from this company is an architect who has been working with innovation since 2000 and developed Building Information Modelling (BIM) standards. All three companies are large, with the resources to test innovative solutions. As such they have the potential to function as role models within the industry.

4. 3D printing technology and its drivers, enablers and barriers

4.1. 3D printing technology

3D printing is a type of additive manufacturing (AM), which can be defined as: "the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" (Standard Terminology for Additive Manufacturing Technologies (ASTM, 2012). Additive Manufacturing AM is a tool that offers increased "design freedom" (Bikas et al., 2016), because it is possible to make parts with intricate and complex geometries. This mean that three important aspects in the use and analysis of additive manufacturing are: material, process, and design which include 3D model data (Labonnote et al., 2016). The 3D printing technology is used in several industries, utilizing different material types. By the 3D printing technology, solid objects can be produced from a digital (i.e. CAD) model. In the process, a series of 2D layers are deposited by a printer (Boothroyd, 1994). The objects are fabricated through the deposition of a material using a print head, nozzle, or another printer technology (ASTM, 2012). From a sustainability perspective, it is attractive that additive manufacturing has near-zero material waste and can utilize a variety of materials. Also, the quality of the parts produced can be assessed using a variety of methods (Stavridis et al., 2018).

There are some examples of applications of 3D printing in concrete. A concrete five-story residential complex was built in China by Winsun (Sevenson, 2015) between 2014 and 2015, for which a giant 3D printer was used to pour concrete layers following a digital model, but the design looks very similar to traditional concrete houses (Brandon, 2015). Several young and innovative start-ups show however a willingness to reshape the way we think about architectural components (Rael and San Fratello, 2011) and to exploit the design potential of additive manufacturing technologies for construction. Among others, Branch Technology (Branch Technology, 2016) patented a freeform printing process to construct complex geometries in open space without the use of support materials, and plans to build a single-family home with sleek cave-like form (Huen, 2017). More complete overviews of previous and current additive construction experiences can be found in (Labonnote et al., 2016; Labonnote and Rüther, 2016; Perkins and Skitmore, 2015; Wu et al., 2016).

4.2. Drivers of 3D printing for implementing in construction projects

A set of drivers that can support project innovation in general, and 3D printing in particular, are identified through a literature review, as described in the methods section. Significant customization opportunities due to design flexibility and strong integration between design and manufacturing, enabling the realization of complex geometries and materials: Construction projects differ in various criteria such as size, geometry, design, material, aesthetic, and insulation requirements. In addition, it is often characterized with the waste of resources and creating significant environmental issues. These factors trigger the hope for the use of AM based 3D printing technology in the construction industry, which can customize the construction projects with high time and cost efficiency (Xue et al., 2014a).

Minimization of waste (e.g. reduce material waste): This has been assessed by Berman (2012), among others, when making comparisons with subtractive manufacturing technologies. It is argued that additive construction produces less waste, and that it also enables the recycling of most of the waste during the next round of additive construction (Rael and San Fratello, 2011; Berman, 2012; Achillas et al., 2015) and this is applied in particular in the case of excess cement and aggregates.

Better carbon footprint: Achillas et al. (2015) consider that the carbon footprint left by additive construction is significantly smaller than that left by traditional construction techniques. In general, less material is used, firstly because of the absence of a requirement for molding and casting operations, and secondly because additive construction enables highly optimized construction processes and the production of highly-optimized components that naturally reduce the amount of material used. When combined with technologies that favour in-situ resources, additive construction is also described as resulting in a significant diminution of carbon emissions related for the most part to transport (Achillas et al., 2015; Strauss, 2013). Bowen (2007) argued that transport-related emissions were further reduced because of the need for less traffic to and from the construction site as a result of limited labour requirements. Haymond and Noble (2008) used the 2008 LEED Homes system as a guide to isolate the sustainable potential of additive construction (in the form of contour crafting) as an alternative to conventional construction for single family housing.

Cost-efficiency: Bosscher et al. (2007) presented a comparative cost and productivity analysis designed to evaluate the potential of their cable-suspended additive construction technology against traditional concrete work. Although the cost savings were considered to be "tremendous" (Rael and San Fratello, 2011; Bosscher et al., 2007) nevertheless concluded that the cost of their additive construction alternative was in fact very similar to a conventional operation, although they did not take into account costs linked to accident and safety training, which are assumed to be considerably lower for additive construction. In 2014, Skanska's Director of Innovation and Business Improvement considered that additive construction using concrete had the potential to revolutionize the entire process of construction, and anticipated that it would "reduce the time needed to create complex elements of buildings from weeks to hours" (www.3ders.org and Loughborou, 2014). The Chinese company Winsun probably shares this view and has claimed in the public domain to save between 30 and 60 percent of building materials and to have shortened production times by between 50 to even 70 percent, while at the same time decreasing labour costs by 50 to even 80 percent. This took place while the company was allegedly applying additive construction to the construction of ten individual houses and a six-story apartment building. However, Brandon (2015) was critical of Winsun's achievements, emphasizing that no description was provided by the Chinese company as to what had in fact been produced, and considered that its figures were highly doubtful. Finally, the issues of low-income housing and third-world housing have been mentioned in the literature. Among other initiatives, Tridom formed a strategic partnership with WASP in Italy in order to investigate the additive construction of affordable and sustainable housing for "bottom-of-the-pyramid" people (Sher, 2014).

Use of 3D printing can reduce danger for human workers in harsh environments, where access for humans is either difficult, impossible or dangerous (MillsapsMillsaps, 2015). Such applications will reduce stressful workloads and prevent fatigue and accidents (MillsapsMillsaps, 2015; Perrot et al., 2016). Two examples of this are provided.

(1) Quick deploy-ability in hazardous situations resulting from either natural or man-made disasters (Peter, 2015). Several potential applications were emphasized, and in particular those focusing on the construction of first response shelters (Howe et al., 2014; Hunt et al., 2014), and the repair of damaged infrastructure (Abdulrahman et al., 2015). The University of Nantes in France has developed the INNOprint 3D printer for this purpose. This printer is capable of building a small emergency facility in just under 30 min that is insulated, sealed, and safe to live in (www.3ders.org, 2015). In such situations, additive construction can also be used to build infrastructure in remote regions with the aim of facilitating access, such as bridges, etc. in discontinuous terrain to assist humanitarian aid (Gaziulusoy et al., 2016).
(2) Relevant technology to build in extra-terrestrial environments: Plans to erect constructions on the Moon have already been proposed. Johann-Dietrich Wörner, who is head of the European Space Agency (ESA), has indicated that his organization is intending to start building "Lunarville" by as early as 2024 (Orwig, 2015) and US President George W. Bush is reported to have announced that the National Aeronautics and Space Administration (NASA) suggested constructing a lunar base by 2020 as a jumping-off point for future missions (WilhelmCurbach, 2014). In addition, Mars is also claimed to be a target for human colonization before the end of the new century (KhoshnevisRussell et al., 2001). Projects involving the construction of settlements on the moon have been highly publicized. They include plans originating both from NASA (Khoshnevis, 2004) from SinterHab (RousekEriksson and Doule, 2012), and from the ESA, in partnership with Foster and Partners (CeccantiDini et al., 2010). It is could be argued that extra-terrestrial environments will demand a significant contribution from additive construction, not least when it comes to facilitating the maximum exploitation of in-situ resources (Kading and Straub, 2015) in order to minimise the enormous costs of transporting materials to construction sites using space shuttles (Howe et al., 2014). Such applications are assumed not only to reduce transportation costs but also to increase the efficiency of extra-terrestrial operations (FateriGebhardt and Khosravi, 2013).

4.3. *Enablers of implementing 3D printing in construction projects*

A number of enablers are identified through the literature review. In order to achieve a recognizably environmentally friendly construction process, a full life-cycle analysis (LCA) of additive construction processes must be performed in the same scientific and objective way this has been already performed for additive manufacturing processes (Drizo and Pegna, 2006). Additive construction is such a wide-ranging concept, involving many different materials and technologies, that it is doubtful if all additive construction processes will be able to reduce carbon footprints to the same extent when compared to traditional construction techniques. Some are probably better than others are. In this sense, "digital" additive construction would also act as a catalyst for the integration of LCAs as a basis for construction projects.

The houses of the future must free themselves from traditional (and less efficient) designs if they are to benefit from the potential inherent in additive construction. In fact, the future of additive construction may rely on an architectural paradigm shift. An important issue for architecture as a field will therefore be whether or not architects are ready to make use of the complex (Gardiner, 2011), potential and the high degree of design freedom (www.3ders.org, 2015) provided by additive construction, and whether or not they will be able to "reshape the way we think about architectural components (Rael and San Fratello, 2011).

In a new building process, for the paradigm shift to take place, project management must consider the production and assembly stages of the construction process right from the start of the design process. Ideally, the design process should be thought of as collaboration between architects, engineers and constructors. All these aspects must be far more incorporated into a single design process if the true potential of additive construction is to be realized.

An evaluation of the cost-efficiency of additive construction must rely on knowledge of the allocation of costs involved in the design phase, material consumption, human labor for construction, and equipment. Unfortunately, overall knowledge of these factors is often incomplete or missing. There is a need for comparisons between existing approaches and new additive construction techniques that are scientifically documented.

Rational decision-making will involve trade-offs, and the task will be made more complex by the large volume of information made available via the holistic design process. However, this will also mean that additive construction should become the next natural step in the evolution of "smarter" construction. By doing so, additive manufacturing technologies would definitely demonstrate an important advantage over traditional construction processes for investing towards a low carbon, resilient and sustainable future (Labonnote and Rüther, 2016).

4.4. Barriers of implementing 3D printing in construction projects

Following barriers are of particular interest. The survival of 3D printing in the construction industry is largely dependent on the degree of customization requirements in the construction industry (Wu et al., 2016). A large demand for customization would increase the demand for 3D-printed products, thus decreasing the printing costs and helping the technology survive in the construction industry. Therefore, the central issue is whether a large demand for mass customization could be expected in the construction industry. The categorization of demands in the construction industry (i.e. either functional or innovative) requires further investigation. Similarly, future research is needed to identify the customer sacrifice gap, i.e. the gap between the desired product and available products in the construction market. As customization options were usually limited by suppliers in order to achieve economies of scale in the construction process, knowing the categorization of demands, the degree of these demands and the customer sacrifice gap will be useful for 3D printing technology to reach economies of scale (Wu et al., 2016).

Due to size limitation of existing 3D printers, it is difficult to print a high-rise building all in one go (Gibson et al., 2002). However, structural components can be printed piece-by-piece and then assembledtogether as a real-scale building (Feng and Yuhong, 2014). When applying this approach, users need to address some critical issues so that building as assemblages of components reflects aspects of real-world material fabrication and assemble methods (Sass and Oxman, 2006).

Firstly, it remains unclear whether 3D printing could lead to reduced or increased construction cost (Wu et al., 2016). The assumed high cost of the 3D printing technology as compared to conventional technology is a particular challenge for small and medium sized enterprises that constitute the majority of the construction industry. The commonly recognized three cost items in construction included labour, material, and plant. While labour costs could be reduced similarly to manpower requirement, 3D printable materials are usually more expensive than traditional ones. In summary, although short-term potential cost reduction can be achieved by 3-D printing, empirical studies are needed to investigate the financial performance of the printed construction product or project over its life cycle.

Secondly, types of materials can be used in 3D printing technology are limited. They should have some basic features such as quick hardening in order to be used in 3-D printing (Wang et al., 2016). There were various studies which found that the strength and stability of the printed products using current printing materials (such as plaster) might prevent the technology from being used in large-scale models or buildings. The low availability of high-strength printing materials also led to the speculation that 3-D printing might not be used in large-scale models or buildings.

Thirdly, the digitalization of designs and manufacturing raises concerns about intellectual property rights (Wang and Rimmer, 2020). The digital files that describing an object and an additive construction can potentially be copied and distributed out of control of the organization which created it (Berman, 2012). The lack of standardization and regulation governing 3D printed objects, whether these are products or the construction itself, has also been noted (Strauss, 2013). Validation should apply in this specific case to both hardware and the construction project in question (Leblanc, 2014). The regulation issue is a serious matter because of the consequences that will be incurred if construction failures result in fatalities. This situation represents a serious challenge if additive construction is ever to compete with traditional construction approaches (Gardiner, 2011).

Finally, the liability issue should also be considered carefully. There have been speculations (Campbell et al., 2014) as to who would be liable in the event of failure of a powder metallurgy fabricated (using 3D printing) component of an aircraft wing. Would it be the original manufacturer, the programmer, or the manufacturer of the new design or new smart material? This problem is even more complicated in the case of building components that may have two or more functions, such as a wall installed with hot water transport and electrical distribution equipment.

3D printing and programmable equipment face the additional challenges linked to cyber security and risk of hacking. Campbell et al. (2014) raised the issue of securing embedded programmable capabilities into objects.

5. Case study interviews

5.1. Innovation and 3D printing experiences of the companies

Company A offers a large portfolio of construction services including architectural services, design, project management, construction services, operation and maintenance, sitework, concrete work, electrical, and plumbing services. They work along the whole value chain but are particularly strong within project management and project development.

The director from Company A claimed that it is a conservative industry with little innovation taking place over the 40 years that he has worked at the company. However, things have happened during the last 5 years at a high speed. This is mostly occurring on the design side in digital drawing and BIM tools. There are also innovations related to industrialization of construction through modularization, which is in high demand and focus. The respondent from Company A stated that materials and concrete are main areas. Low-carbon concrete, virtual design, use of sensors and digitalization are currently in focus within the company. The Norwegian respondents from Company A didn't know whether they have been involved 3D printing. There is no strategy in the Norwegian facility for implementing 3D printing. They are watching what is happening in other companies and other countries, for example in EU, which is more active in implementing 3D printing.

Company A's EU facility has experienced innovations in digital engineering, offsite fabrication, design, and manufacturing efficiency. This was stated by the informant associated with the EU facility. There are currently projects on BIM, 3D printing, geographic information systems, and automation and robotics. All the projects mentioned are collaborative and they have all received external funding and can be classed as research projects. The EU facility has been involved in 3D printing for 2–3 years. The motivation is that they can produce very high-quality building components easily and cheaply. They are focusing on printing complex parts. Parts that are impossible to create other ways. Cladding is the most applicable solution. There are benefits when working with complex shapes and continuous variations – continuously varying facades that are impossible to make any other way. There are many technical challenges still existing, and aesthetics is an important issue. To overcome the challenges and achieve the preferred aesthetic quality there is a need for both subtractive and additive processes. Reinforcement is another challenge where solutions are on their way.

Company B also offers a broad range of services and is considered as a competitor of Company A. The company works primarily with construction but also designs buildings and provides facility management. The respondent from Company B has experienced innovation in many areas as he has been working at the R&D department. Among others, the following areas were emphasized: materials and production, design, energy and sustainable solutions, robotics, environmental design and biodiversity, circular economy. There are also some ongoing projects within these topics, such as a Horizon 2020 project which is about how to remove asbestos, and a project that looks at how to imagine biodiverse solutions for roofs. Company B is involved with experimental projects and prototyping for 3D printing. 3D printing is part of the company strategy but is allocated a small budget. A group is working on 3D printing. There are 3 projects linked to concrete, but no metal and plastic at the moment.

Company C works with architectural services. The respondent from Company C has emphasized their innovation efforts within process thinking, standardization, and added value in construction. BIM for information workflow has been the major innovation for this purpose. Data capturing is becoming more and more efficient and is now including information for the entire building operation. They are becoming more innovative about how they capture data. Now there is easy access and the data is more correct. Company C is prototyping and making models for customers by 3D printing. They are making plastic and plaster models. Models give good feedback to architects. It is a report form, like a drawing, another way of reporting from BIM.

5.2. Enablers and barriers of implementing 3D printing innovation

Interviewees have largely agreed on the main enablers for innovation. All respondents stated that effective leadership, collaboration with partners, and industry-academia collaboration are primary enablers of 3D printing innovation.

Company A pointed out the importance of leadership and customer commitment for successful implementation of 3D printing. The company's EU respondent prioritized R&D funding and collaboration before the leadership commitment. If it is high quality and cost-efficient it will attract the leaders. Customers should also want 3D printing in buildings. The director from Company A also pointed out the significance of supply chain thinking for innovation. Clients ask for projects where the supplier is involved. Contact with the supply chain is therefore necessary, from the architect to those who are going to deliver afterwards. The environmental aspect is also a driver, not only for sustainability but also economy because it has a positive effect on the sale and rental of buildings. The second Norwegian respondent included the importance of collaborating with researchers on the projects and allocating a budget. According to the EU respondent from Company A, the main driver for innovation is to become more competitive and having a dedicated innovation capability and funding. They currently have four fulltime innovation managers and 20 people work with this part-time.

In terms of barriers, Company A respondents discussed the conservatism of the construction industry and have different points of view. According to the Norwegian director in Company A The industry is conservative because no one has demanded anything There is always an element of risk when testing new technology and here is need for new contracting models to mitigate and share risks. According to the second Norwegian respondent from Company A, about the idea that the construction industry is conservative is a misunderstanding. Customers ask for something that is innovative, and then the company makes it. The respondent from the EU facility of Company A said that the construction industry is conservative, but this is changing. Historically it has gone through big cycles. Now they see the benefits and solutions, there is a lot more customer pull, asking for innovation. The respondent also emphasized the complexity of construction in terms of an important barrier. It is difficult to come up with widely applicable solutions because of the complexity. In addition, there is a lack of funding and supply chains are fragmented. finally, there is a culture for localized problem solving but no culture for universal solutions or widely applicable solutions. Innovation happens in individual projects.

The respondent from Company B also stated the importance of having a strategy for open innovation. Governmental regulations are a very good driver to push clients and companies. More and more of the bosses are convinced that sustainability in terms of the circular economy - cannot be avoided. It is a good reason to innovate and many projects are linked to it. The respondent from Company B claimed that the leadership is important, but if the client and market do not want it, then it will not happen. He added that sharing information is important, such as codes and patents. The respondent from Company B has also pointed out the conservativism of the industry in terms of barrier, which can be problematic in spreading information through teams. Construction professionals are strong and experienced, but it can be difficult to change their minds. The focus on cost efficiency and funding can also be a barrier. The industry is not patient. Most planned actions begin with what is likely to be successful and leave to the end the more difficult issues. People often rush in with what they know how to do – it is a culture of quick gains. People get tired and are not interested when the difficult stuff starts. There is also a belief that every building is unique, and that innovation is a one-shot experience. It is difficult to get people to see innovation as a long-term issue. Being technology-driven might also make innovation fail. There should be a focus on the problem first.

The respondent from Company C claimed that leadership commitment is important but there is need for demonstrating how this will work if it is worth the investment. There is no need to 3D print everything. Complex parts could be 3D printed. This goes hand in hand with industrialized development and offsite construction. There is a need for standardized interfaces. In terms of barriers, the respondent of company C also emphasizes that if you believe too much in technology and not enough in the people thinking, it will not work. Things can go wrong if there is a lack of leadership. Small focused steps are important. Make sure it works before you move onto the next one. It is also always a struggle to change an organisations behaviour and culture. There is a lack of competence, a lack of interest and understanding about how technology can improve a product and productivity. There is an understanding that risk is involved and a lack of understanding about how it could mean developing your company.

6. Case study interviews discussion

The case study interviews outlined the key enablers and barriers for implementing 3D printing in construction, as summarized in Table 3. They also point to drivers and barriers that could influence acceptance within project-based project management. The enabler highlighted by most companies is effective leadership, in addition to cost efficiency. The leadership issue shows the importance of project management, but also senior executive management commitment. As the main barrier, most companies pointed to conservatism of the industry, along with culture and team focus. Despite the positive expectations about 3D printing technology, the interviews point to the Norwegian construction industry being a bit slow adopter of this technology compared to other EU countries. Then study indicate a degree of sitting on the fence and waiting to see what the rest of the industry or other EU countries are doing, and in particular to study if the technology is profitable. This could also be considered a case of learning from what the other actors are doing. However, key actors must most likely serve as champions for this type of technology, and some of the companies in this study have the potential in terms of size to be a role model.

A conservatism of the Norwegian construction industry can be linked to the high labour costs, which may cause high investment cost

Table 3
Key enablers and barriers identified through interviews.

Key Enablers and Barriers	Company
Key enabler	
Effective leadership	A, B, C
Collaboration with partners/supply chain	A, B
R&D funding and budget allocation	A
Quality and cost efficiency	A, B, C
Customer demand	A, B
New contracting models to mitigate risks	A
Strategy for open innovation	B
Governmental regulations for sustainability	B
Incremental implementation	C
Key barriers	
Conservatism of the construction industry	A, B, C
Risks of implementing new technology	A, C
Complexity of the construction projects	A
Non-standard nature of construction projects	A, B
Fragmented supply chains	A
Lack of funding	A
Culture of local focus and teams	A, B, C
Technology focus, ignoring other factors	B, C

expectations for the 3D printing technology.

The conservatism of the construction industry to adopt 3D printing can also be compared with other industries in Norway, where Industry 4.0 and 3D printing is on its way to acceptance. According to the Norwegian Industry Report from 2016 (Norsk Industri, 2016). Companies from automotive aluminium and plastic industries are currently utilizing the potential with 3D printing as a production method.

While 3D printing is mainly being used for prototyping, it is becoming an important method for making of the tools, fixtures, spare parts, as well as producing parts and repairing the equipment. According to the report by Norsk Industri (Norsk Industri, 2016) 20% of the manufacturing companies use 3D printing for prototyping while fewer use 3D printing for ordinary production. In terms of materials, plastic and ceramic appear to be widely used in 3D printing, but there is a major development in 3D printing of metals.

Previous innovation experiences imply valuable insights and learnings for the introduction and implementation of the 3D printing technology to the construction industry. These implications are summarized in Table 4, taking the characteristics of the 3D printing innovation.

We find that 3D printing has characteristics that support successful implementation in construction projects, but also shares many of the characteristics that have created challenges in previous innovation initiatives in the sector. In particular, it is important to demonstrate the potential profitability of the technology.

3D printing, and other aspects of Industry 4.0 may have social effects. To construction workers, it is a challenge to acquire new technological knowledge. To those who manage new technologies they represent an opportunity, while those who struggle to work with and understand new technologies may have challenges on the labour market. From a user perspective, more efficient production of for example homes would be a benefit as it can influence the cost of living.

Table 4
Implication of barriers and enablers on implementation of 3D printing.

Previous experiences	3D printing characteristics	Implication for implementation of 3D printing
Focus on cost efficiency of the projects and lack of funding in R&D	3D printing technology is getting funding for R&D	The large funding will facilitate to implement it on large scale in construction industry
Mismatch between market needs and innovation	3D printing will facilitate the mass customization in construction industry	As mass customization has high demand in construction industry, this feature of 3D printing technology should be leveraged in improvement projects.
Lack of skilled workforce in the market for innovation implementation.	High-skilled labour required for 3D printing operation	High-skilled labour is a big challenge to implement the 3D printing technology on large scale. Training and education initiatives are required.
Initial high cost of the innovation	High cost of 3D printing technology	Especially, the SMEs will have difficulties to afford the 3D printing technology. Actions to improve the technology and reduce the cost of it should be taken.
Risk in adopting new technology	The 3D printing technology is not mature for large scale usage	High risk is involved for large construction companies to use this technology at large scale. New risk sharing models will be of importance.
Non-profitability	3D printing has capability of waste reduction, cost reduction and time reduction	The use of 3D printing will result in more productive and profitable projects, which should be escalated for wider implementation.
Multiple stakeholders create challenges for collaborative implementation of the innovation	Multiple stakeholders are involved in the implementation of 3D printing	Implementation of 3D printing technology requires a common understanding and interest within the whole construction value chain.

7. Conclusion

In specific, this paper contributes to the literature and practice by outlining drivers, enablers and barriers of implementing 3D printing in construction projects, through a comprehensive literature review and interviews with industry practitioners. In general, we discuss 3D printing as an application of Industry 4.0 in a project context. We treated drivers as factors that push organisations to innovate, while enablers represent factors that support innovation. Barriers are factors that make innovation difficult. The study results indicate that the construction industry in general needs more examples of the projects that show the cost efficiency obtained by the implementation of the 3D printing technology. This will increase the awareness of this technology and adopt it to a larger extend. The construction industry is considered to be conservative, which can partly explain slow adaption of Industry 4.0 and related concepts.

The interview participants put the cost efficiency of 3D printing forward as a key enabler for larger adoptions of this technology in the construction industry. In terms of project management, 3D printing has potential to improve the construction processes, make them more effective, by saving time and money, but investment costs are high and support from leadership is required. R&D is a central factor for encouraging investment and prioritisation. It does this by producing good or ambitious examples and shows how things can be done. This issue brings another important mission to the research projects to demonstrate the efficiency gains by implementation of 3D printing in use cases. It is likely that the specific results related to 3D printing are an indication of challenges for implementation of other parts of Industry 4.0 in project businesses.

Declaration of competing interest

Javier Alonso Madrid does R&D and consulting on innovative technologies, including 3D-printing. The other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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