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Sustainability tradeoffs in the adoption of 3D Concrete Printing in the construction industry

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ABSTRACT

In recent years, 3D Concrete Printing (3DCP) has gained traction as a technological solution for reducing cement production's hefty carbon footprint. Studies assessing the sustainability benefits of 3DCP have not included its impact on social sustainability, nor how construction firms' implementation of this new technology has affected its success. This study applies grounded theory methods to analyze the tradeoffs between environmental, economic, and social sustainability, and how firms' decisions impact these tradeoffs. We gather insights from 20 interviews with 3DCP pioneers in Central and Northern Europe. Our findings suggest that firms' greatest incentive to invest in the technology is not related to the environmental benefits, but rather 3DCP's potential to increase automation and combat the current shortage of skilled labor in the construction sector. Current government procurement rules do not reward sustainability benefits sufficiently to encourage the uptake of 3DCP. Based on our findings, we identify five strategic decisions that companies make which affect 3DCP's sustainability, and discuss opportunities for government to foster the adoption of this technology.

1. Introduction

The construction sector is an important engine of economic growth, but also a resource-intensive industry and major contributor to greenhouse gas emissions. The United Nations (UN Environment 2019) estimated that the construction industry accounts for 36 percent of global energy consumption and 39 percent of global energy-related CO2 emissions. This environmental footprint, frequently measured through lifecycle assessments (Onat and Kucukvar, 2020), is expected to worsen in the coming decades, as global urbanization trends outpace efforts to promote energy efficiency (Miller et al., 2016). The construction sector's key culprit in releasing greenhouse emissions is concrete production. Concrete is the second most used substance in the global economy, after water (Gagg, 2014), thanks to its low cost, high fire resistance, and compressive strength. The production of cement alone, one of the main components of concrete, is estimated to account for 5 to 7 percent of global CO2 emissions (Shanks et al., 2019). Producing concrete also requires copious amounts of water, estimated at roughly 9 percent of global industrial water withdrawals (Miller et al., 2018). The overexploitation of sand, another key component of concrete, has led to a situation of global sand scarcity (Torres et al., 2017).

A technological opportunity to improve the sustainability of concrete structures is the use of 3D Concrete Printing (3DCP). Proponents of 3DCP argue that the technology can sharply reduce material usage and waste (Mechtcherine et al., 2019), raise productivity (Weng et al., 2020), and combat the skilled labor shortage facing the construction sector (Kim et al., 2020). Empirical analyses have focused on the quantification of potential environmental and economic benefits, using techniques such as lifecycle assessment (Agustí-Juan et al., 2017; Alhumayani et al., 2020; Han et al., 2021), and technical cost modeling (Weng et al., 2020), based on case studies. Such analyses, however, have not taken into account the effect of 3DCP on social sustainability; nor why managers decide to implement 3DCP in their companies, and how their decisions can create tradeoffs. Given it is mainly governments that commission large construction projects, and are thus responsible for regulating the market, the existing institutional framework likely exerts a large influence on whether 3DCP is adopted by companies, and therefore the ultimate sustainability benefits. Previous studies lack an analysis of how the institutional framework influences construction management decisions concerning 3DCP.

We contribute to the literature by analyzing how managers' decisions on implementing 3DCP in construction projects affect the tradeoffs between environmental, social, and economic sustainability; and how the current institutional environment affects managers'

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incentives to invest in 3DCP. To answer these questions, we used grounded theory methods (Corbin and Strauss, 1990; Glaser and Strauss, 1967). Our findings are based on 20 interviews with 3DCP pioneers in Central and Northern Europe. We divided our analysis across the triple bottom line dimensions of people, planet, and profit (Elkington, 2008).

Our analysis revealed that current sustainability requirements in government tenders are not stringent enough to promote the adoption of 3DCP. Aspects relating to social sustainability, overlooked in previous studies, could arguably be the major driver for adopting 3DCP. We identified not only the major decisions that companies need to make when implementing 3DCP, but also the impact of those decisions on sustainability, and how policy can accelerate the uptake of this technology.

2. Background

2.1. 3DCP promises and challenges for the construction sector

Here the term 3D Concrete Printing (3DCP) refers to various technologies that create objects by depositing concrete layer-by-layer until the final desired geometry is achieved (Paolini et al., 2019). The working principles of 3DCP machinery are similar to those of 3D printing with materials such as polymers or metals. However, the structures built using 3DCP, such as walls or entire floors, are much larger than the components typically printed with polymers or metals. The larger the size of the printed components, the greater the likelihood of minor flaws occurring during the printing process, thus increasing the complexity of establishing a robust quality control process.

The most attractive aspect of 3DCP in construction is the opportunity to create complex geometry without the need for additional formwork (Mechtcherine et al., 2019). Depending on the type of project and location, formwork can account for more than 10 percent of construction costs (Mansuri et al., 2017). Formwork, commonly made from timber, represents a major source of waste, since there is a limit to how many times it can be reused (Jaillon et al., 2009). With 3DCP, the printing process can be configured to minimize material usage. By cutting down the need for raw materials, 3DCP can significantly reduce the large environmental footprint associated with construction activities and concrete fabrication (De Schutter et al., 2018). 3DCP also gives architects more freedom to experiment with novel geometries in buildings, which can be optimized in order to improve their energy efficiency or air flows, thus reducing the environmental footprint during the built environment's entire lifecycle (Rael and Fratello, 2018).

Besides material savings, 3DCP guarantees economic benefits relating to automation. Productivity in the construction sector has stagnated in recent decades due to low technology sophistication and high levels of manual labor (World Economic Forum, 2016). Furthermore, the construction industry in the West is experiencing labor shortages (Karimi et al., 2018; Kim et al., 2020). This shortage can be offset by bringing in seasonal workers from less developed countries, but they are particularly vulnerable to social and work-related problems (Alberti and Danaj, 2017). In the worst case scenarios, criminal networks end up trafficking and exploiting undocumented or illegal construction workers (Cockbain and Brayley-Morris, 2018).

Governments and firms have proposed ways to increase productivity and reduce the need for scarce labor, including a greater share of prefabrication and off-site construction (Durdyev and Ismail, 2019), as well as increased digitization of construction activities across the entire supply chain (Leviäkangas et al., 2017). In particular, the automation of the construction process has the potential to eliminate the structural flaws and inconsistencies that occur with manual labor. The rework costs of these defects are seen as a major source of uncertainty in construction project planning, and may account for between 5 and 15 percent of the total project costs (Forcada et al., 2017). Furthermore, 3DCP equipment could potentially, under minimal supervision, operate at night or in harsh environmental conditions, when manual construction activities would usually stop.

Despite 3DCP's potential to enhance sustainability, the technology is not without its drawbacks. A major limitation is the lack of material choices available to constructors (De Schutter et al., 2018); the material mixes for 3DCP are only basic formulations that do not differ significantly from traditional mortar, but have substantially different rheological properties (Lucas and Barroso de Aguiar, 2019). On-going research to increase the sustainability of concrete for 3DCP is developing alternative binders such as geopolymers (Ur Rehman and Sglavo, 2020), fly ash (Alghamdi et al., 2019), or limestone (Chen et al., 2020). More sustainable supply chains are needed to ensure the production, distribution, and recycling of 3DCP materials (Despeisse et al., 2017).

In addition, the mechanical properties of printed components are typically poorer than casted concrete, and are highly sensitive to minor changes in manufacturing process parameters (Wolfs et al., 2019). This variability limits the range of where 3DCP can be applied. Furthermore, 3DCP pioneers will likely require a large investment in R&D, and a long period of trial-and-error, to establish robust quality control and reduce variability in production (Argote and Epple, 1990; Bohn, 2005). As observed in other industries that have already adopted 3D printing technologies, designers will also need time and retraining to learn how to exploit 3DCP's full potential and achieve the environmental benefits of material savings (Assunçao et al., 2019; Blösch-Paidosh and Shea, 2019). New technical standards will have to be developed, compliant with existing regulations (Bonnín Roca et al., 2017; Seifi et al., 2017). Novel testing methodologies are also needed to ensure the long-term durability of 3DCP materials (Lu and Wong, 2018).

Studies examining the sustainability of 3DCP (Agustí-Juan et al., 2017; Weng et al., 2020) emphasize its benefits, whereas works describing 3DCP's limitations (Alghamdi et al., 2019; Bos et al., 2016; Wolfs et al., 2019) tend to focus on the technical aspects, not sustainability. The environmental and economic assessments of 3DCP, usually computed through lifecycle assessments (Han et al., 2021; Weng et al., 2020), ignore aspects related to social sustainability, and are limited to single case studies, without looking at industry-level factors such as regulation and culture. These contextual factors can have a considerable impact on how a technology is adopted (Venkatesh et al., 2011), the sustainability of the business models (Maltz et al., 2018), and therefore the extent of the sustainability benefits (Bergek et al., 2008). To date, the literature has not provided a holistic view on how 3DCP creates interactions between the triple bottom line dimensions, even though these interactions are critical for assessing its overall sustainability. This paper contributes to the literature by adding social sustainability to the assessment of 3DCP's sustainability, and by analyzing to what extent managers and designers' decisions influence the tradeoffs between environmental, social, and economic sustainability.

2.2. Institutional environment affects 3DCP uptake

Certain features of the construction sector hinder the introduction of 3DCP: R&D spending levels are low (Spithoven et al., 2010); a shortage of skilled labor, partly due to the lack of specialized training programs, and the low attractiveness of construction as a career path for young people (Kim et al., 2020); profit margins are low and volatile, so managers tend to be conservative when adopting new technologies (Giesekam et al., 2016; Tezel et al., 2018). Consequently, R&D focus in the construction sector is on incremental innovation, and efforts geared to sustainability are often market-driven (Weber and Schaper-Rinkel, 2017). To help overcome industry's aversion to risk, governments have developed policies and legislation to incentivize companies to increase their sustainability (Kylili and Fokaides, 2017).

Government, as the main client in large construction projects, can use public procurement to foster innovation and sustainable practices (Wesseling and Edquist, 2018). Procurement rules could be modified, for instance, to mandate a specific technology for a project, or to establish responsibility for waste management and a recycling plan

(Lăzăroiu et al., 2020; Sparrevik et al., 2018). Common practice is to specify thresholds for the maximum allowed level of environmental damage generated during the project, usually quantified with standardized indicators that estimate the project's environmental performance (Hossain and Ng, 2018; Subedi et al., 2018). An advantage of such performance-based indicators is that instead of being obliged use a specific technology, firms are free to decide which solution best suits their particular context to meet the specified threshold (Coglianese et al., 2003). If the regulatory limits cannot be met with existing technology, they may have a technology-forcing effect, inducing firms to adopt radical innovations in order to meet sustainability goals (Ashford and Hall, 2011; Lee et al., 2010).

Procurement rules are often linked to technical standards and building codes. Government may opt for stricter technical standards to foster innovation across the entire supply chain (Ozorhon et al., 2014). In fact, new technologies' compliance with existing standards has proven to be a key driver of technology adoption decisions in construction (Giesekam et al., 2016). However, while standardization has greatly improved safety in construction and homogenized practices across firms, excessive reliance on standards can mean that technological solutions which are incompatible with those standards never reach the market (Dekkers, 2000). In the case of 3DCP, the design scope it allows may clash with existing standards that favor prefabrication assemblies of given geometries, where quality can be more tightly controlled during the manufacturing process (Linner and Bock, 2012; Said, 2015). This conflict between 3D printing technologies and technical standards has also been observed in other highly-regulated industries such as aviation, biomedical, or automotive (Seifi et al., 2017; Thomas-Seale et al., 2018). Based on experience from other sectors, developing standards for 3DCP in construction will likely require coordination between public and private actors (Seifi et al., 2017; Wiegmann et al., 2017).

Overall, the institutional environment where construction firms operate is expected to greatly influence whether firms decide to adopt 3DCP, and thus the extent of sustainability benefits. This institutional environment may vary greatly across regions (Zeitlin et al., 2000). Existing studies analyzing the sustainability of 3DCP (Alhumayani et al., 2020; Han et al., 2021; Weng et al., 2020) have not incorporated the influence of the institutional environment. Our paper contributes to the literature by providing insights on how managers perceive the institutional incentives to adopt 3DCP in the Netherlands. We expect our findings to be applicable to other European Union (EU) countries, given that sustainability goals and building codes (Eurocodes) are harmonized among EU members.

3. Method

This study used grounded theory methods (Corbin and Strauss, 1990; Glaser and Strauss, 1967) to analyze the sustainability tradeoffs when adopting 3DCP, and whether its uptake is incentivized by the existing institutional framework. Our findings are based on 20 semi-structured interviews, lasting between half an hour and 1.5 h. Most interviews (18) were conducted via videoconference, as work and travel restrictions due to the Covid pandemic limited interviewees' availability; the remaining interviews were held face-to-face. Interviews were conducted in English and in Dutch (translated into English), recorded, and transcribed. The interviewees were selected to provide a balanced representation of stakeholders involved in the adoption of 3DCP (Seawright and Gerring, 2008). In particular, we approached innovation and environmental managers at construction companies, two suppliers of 3DCP robotic equipment, material scientists, structural engineers, innovation consultants, an architect, and a member of parliament. Appendix A presents the list of interviewees and their background. The authors prepared an interview protocol (see Appendix B), which was divided into four sections. The first section aimed to gain a better understanding of 3DCP's characteristics and the challenges with its implementation. The other sections focused on how 3DCP implementation impacts each of the triple bottom line dimensions.

All of our interviewees had firsthand experience with at least one completed 3DCP project or pilot. Our first round of interviews was held as a result of reaching out to stakeholders involved in Project Milestone, the world's first commercial housing project built with 3DCP, in the Dutch city of Eindhoven. The purpose of this first round was to better understand the technical and financial problems that arise when attempting to take the technology from lab to market. The first group of interviewees helped us snowball sample (Noy, 2008) the rest of our interviewees. Our approach in the second round was to discover the sustainability tradeoffs with 3DCP, how it compares with alternative technology solutions already available to firms, and what technical improvements are required to ensure 3DCP's long-term viability. To prevent biases in the snowball sampling that could inflate the consensus across interviewees, the authors attended the international conference 'Digital Concrete 2020' that provided an opportunity to engage with researchers and practitioners not directly linked to our initial interviewee sample. Following advice from Low (2019), our theoretical saturation point was reached when the last 5 interviewees, who came from 4 different organizations, did not generate new categories that were relevant for our unit of analysis, in this case 3DCP.

This research was performed in collaboration with a construction industry contractor, from now on referred to as the 'focus firm.' This focus firm is a large company carrying out both housing and public infrastructure projects, and its 2019 revenue exceeded one billion euros. The focus firm has participated in several pilot programs using 3DCP to produce test components. Our collaboration with the focus firm was for three months, and included weekly, sometimes biweekly meetings, to discuss our preliminary findings and exchange insights on the potentially most promising applications for 3DCP. These meetings, adding up to about 25 h of interaction with the focus firm, were not recorded, but we were able to take notes. Furthermore, access to the focus firm's internal documents enabled us to better understand how the construction industry evaluates R&D projects, and how technology adoption decisions are made. This helped us validate our findings regarding 3DCP with earlier innovative projects in the construction sector.

Coding of the interviews was done iteratively through data collection, to help us refine our interview protocol. Coding was performed independently by the first author, who also conducted most (17) of the interviews, and the second author, who was able to offer a less biased perspective. Axial coding (Corbin and Strauss, 1990) gave the codes a structure. Interviews were coded line-by-line, following recommendations by Charmaz (2014), applying constant comparison across interviewees according to their sector and organization. Coding was performed manually in three stages. First up for coding were the technology's characteristics relating to sustainability, which were validated against existing technical literature on 3DCP (Section 2.1). The second stage was mapping these technology characteristics to their effect (positive or negative) on the triple bottom line dimensions. These effects are presented in sections 4.1 to 4.3, and Table 1 in section 4.4 is a summary of the coded categories. The third stage involved identifying the cells in Table 1 which contained both positive and negative effects, and linking them to five decisions firms need to make when adopting 3DCP. Section 5.1 discusses these five strategic decisions and their impact on the sustainability dimensions.

Intercoder agreement, assessed at all three coding stages, was higher than 90 percent. In general, our pool of interviewees, regardless of their affiliation and sector, agreed on the definition of the relevant categories. However, at the same time, there was a polarization in their views on the true potential and overall sustainability of 3DCP in construction. These disagreements were found even among members of the same organization—ultimately what motivated us to write this paper.

4. Findings

4.1. Environmental sustainability: good potential, but concerns about full circularity

Our conversations with construction managers revealed that how much they use environmentally-friendly technologies depends on achieving a delicate balance between the environmental benefits and the cost of achieving those benefits. The final decision relies heavily on the government tendering process, as government is usually the key party in large infrastructural projects ("*The decision-making is therefore often at project or tender level, so the tender manager or project manager must therefore be convinced of the added value*"). In most cases, the project will be awarded to the candidate with the most economically advantageous tender (MEAT). Governments may modify tender conditions to include environmental aspects such as the expected contribution to climate change, acidification, or water eutrophication across the entire lifecycle (Cheng et al., 2018). In the Netherlands, MEAT criteria are typically established on a project-by-project basis. Applications are evaluated twice. The quality of the tender is initially evaluated by teams of independent experts who do not have access to the tender's final price. These qualitative assessments are sent to the procurer, who links them to their price.

To compute the MEAT price, each of the materials used in the project has an associated environmental cost indicator (ECI). The ECI introduces a shadow cost per kilogram of material used, taking into account how it is produced, how far it has to be transported, and what happens with the material at the end of its life. To calculate the total ECI cost, contractors need to either purchase the material from a certified source, or obtain the certification themselves. In the case of 3DCP materials, these certifications do not exist. Given that the expected volume of 3DCP would be only a small proportion of the entire materials used in a project, companies are not incentivized to undergo the certification process. "*For concrete, we first have to get all kinds of certificates and it takes a lot of time, so you cannot easily implement it … it does not always have to be cheaper, it can also have a better environmental score … [but] we are not there yet.*" Certification is furthered hindered by the fact that the composition of the currently rapidly evolving 3DCP blends is proprietary to a handful of material providers, for whom these blends are an important source of competitive advantage.

To be effective, MEAT allowances and ECI scores should represent values that encourage innovation and technological change. However, our interviewees agreed that "*the [ECI] values that are now set as maximum are so high that in practice, you are almost always below them.*" Consequently, there is no real sense of urgency about reducing the environmental impact. However, one interviewee saw an opportunity for 3DCP in a small number of tenders where MEAT is not the main criterium. They highlighted "*a tender in which, on a scale of 0 to 100, 50% of your plan is assessed on image/quality (aesthetics), 35% on flora/fauna, environmental nuisance, road safety, etc. and 15% on price. So you have to invest in image/quality to win.*" In such tenders, applicants would not be encouraged to use 3DCP as a way to reduce ECI scores, but rather to exploit 3DCP's capability to create complex geometries that are more respectful of local ecosystems and minimize the visual impact.

Despite being too low at present, ECI scores are expected to become stricter in the future, to foster circularity. The construction industry foresees that by 2050, all tenders will require construction materials to be circular, in line with EU plans to achieve climate neutrality by that year (European Commission, 2020). To comply with future rules, all major Dutch construction companies have announced their strategic plans for circular construction.

Regarding circular concrete, 3DCP presents tensions between opportunities and challenges that are not easy to solve. A major issue in concrete construction is that "*the demand for material is greater than what becomes available secondary [recycling],*" due to the large amounts of waste, and the need for formwork. 3DCP, by radically reducing the amount of materials used, eliminates formwork ("*if I need less material, I also have less material to make circular*"). That said, reducing material usage is not enough, if there is no way to "*re-use those materials and start printing 3D again.*" A potential solution to the problem of recycling, is to develop new material mixtures which contain less or no cement, and that can be more easily treated at the end of their lifecycle. While academic and corporate researchers are working on developing such mixtures, there is still substantial uncertainty about the outcomes. Several interviewees said they were considering using alternative materials such as wood or composites to replace concrete structures. One manager we interviewed suggested: "*it is better to invest time and energy in these kinds of concepts than in a technique/material that by definition can never be sustainable,*" but did recognize that "*we must continue to use [concrete] because for certain applications, there is no fully-fledged alternative.*" Nowadays, concrete is attractive not only because of its price, but also its durability and strength, and finding a substitute is hard. "*In civil concrete construction, production is fully functional, and all concrete is there because of its strength.*"

In addition, 3DCP brings a design freedom that clashes with the principles adopted by construction companies to achieve circularity. One of those principles is creating structures that are highly modular and easily demountable, so that individual components can be replaced without redoing an entire section of the structure. This modularity is at odds with the design freedom and productivity advantages of being able to construct an entire structure at once, with little assembly. "*Building demountable also means something for your design, because then the connection will be different than if I collapsed it all in a monolith … with 3D printing it is all baked together.*" While modular designs become circular more easily, consolidated designs reduce weight, extend component life, and achieve higher functional performance (Yang et al., 2019). Joints between two components introduce structural weaknesses, and therefore require additional material to ensure their integrity.

Regarding 3DCP's potential to reduce the construction industry's environmental footprint, the technology appears to be a substantial improvement over the current situation. However, there are several unknowns about how 3DCP could, in the long term, meet circularity requirements. Whereas alternative materials are an option in certain situations, it is unclear whether concrete can be fully replaced.

4.2. Social sustainability: less reliance on seasonal labor and more satisfied building users

Currently, the Dutch construction industry relies heavily on seasonal foreign labor. "*If you look at civil concrete construction, such as iron braids, they [workers] are mainly Bulgarian or Portuguese and you hardly see any Dutch.*" Labor is imported because it is cheaper than hiring nationals, and there is a shortage of construction workers in the Netherlands. Managers do not see this situation as sustainable in the long-term. The seasonal workers' countries of origin are expected to experience economic growth, and labor costs will rise. Moreover, the labor shortage is anticipated to worsen in the coming decades. These two trends are seen as the major drivers for pursuing automation: "*In 20, 30 to 40 years you will have few people who still understand the profession, so you will have to switch production … you can see that the number of people learning a trade like carpenter is decreasing, there are only a few.*" From this perspective, the technology would not be forcing employees out of the market; on the contrary: the labor shortage would force the technology into the sector. By reducing the need for seasonal workers, 3DCP would also be helping to remove the social problems arising from the instability of seasonal workers' employment, the difficulties in integrating their lives in foreign societies, and the potential risks of immigrant employee exploitation.

The number of jobs affected by substituting traditional concrete-pouring tasks with 3DCP components would vary considerably, depending on how 3DCP is used. Currently, there is considerable uncertainty about whether 3DCP should be done on-site or off-site (prefabricated in a factory). If used off-site, 3DCP would become just another technology applied during the prefabrication of modular components that are then assembled by a squad of workers at the construction site. In countries like the Netherlands where a large proportion of the total construction volume is prefabricated, the impact on labor would be small, and limited to specific professions such as carpenters (as wooden formworks for pouring concrete would no longer be needed). However, the impact in other countries, where there is proportionally much less prefabrication, would be greater. If 3DCP is used directly on site, in theory a large-enough robot could print the entire building structure. In that case, a larger number of employees would be affected, because labor would only be needed to install and calibrate the robotic equipment, and oversee operations. Labor would still be required to install plumbing and electric equipment that cannot be automated at present.

3DCP is also expected to have a positive effect on workers' safety ("*Making formwork is relatively unsafe, more than one carpenter has lost a finger doing woodwork or sawing*"). Even if an accident occurs handling 3DCP equipment, the employee's injury will be much less severe ("*A printer may break, but [nobody] will be injured or die*"). When 3DCP is used off-site, the risks to factory workers are similar to current prefabrication methods. The risks with off-site construction are considered much lower than on-site, given the reduction of work-at-height tasks, and full control over the production environment (Ahn et al., 2020). This contrasts with the disorder sometimes seen on site during large construction projects, "*in the busy times … there are about 150 people walking around outside. That is still a lot of people on site. I wonder if 3DCP printing will help us there.*" By reducing the congestion and interaction between workers, 3DCP could presumably reduce the number of accidents when it is implemented on-site.

For these benefits to be realized, it is critical to create specific training programs. In fact, the lack of training was perceived as one of the major barriers to the widespread adoption of 3DCP ("*I don't think you can find [skilled labor] … If you want to do it [3DCP] yourself, you will also have to train your own people*"). While universities have started preparing the first courses teaching students how to design 3DCP structures, currently there is a lack of professional training programs.

Besides affecting the workforce, 3DCP may improve the functionality of a building for its final users. A key opportunity is increasing a building's thermal efficiency. Although concrete is a poor insulation material, with 3DCP it is much easier to create hollow structures, which can then be filled in with better insulators. In addition, buildings can be designed to optimize parameters such as lighting, ventilation, or acoustics, that are dependent on the building's location and use. 3DCP guarantees that it can "*add this integration without adding the extra costs,*" which requires a holistic approach to building design. In principle, being able to achieve this complete integration of a building would improve its users' quality of life and comfort, reduce energy consumption, and therefore the energy bill.

However, two of our interviewees mentioned that moisture management remains one large obstacle in the implementation of 3DCP structures. Unlike other wall surface materials such as gypsum, concrete does not 'breathe'. This can be a significant problem in very humid areas, where it is important to maintain a balanced amount of moisture throughout the day. Conversely, in very cold areas where water can freeze, it is crucial that no water drops enter the concrete structure, to prevent structural damage. Currently, these problems are solved by applying special surface treatments. Another potential solution is adding structural elements to the walls such as rain screens during construction. Whatever solution is adopted unavoidably depends on the location of the building, as it also needs to comply with local building codes.

4.3. Economic sustainability: large R&D investments due to immature technology

All our interviewees agreed that, in the current state of maturity, 3DCP is probably not cost-competitive against traditional concrete pouring techniques, "*you see all these companies … stating that you can print a house in 24 h or 48 h. This is just a marketing stunt, …I would ask if the guy who printed the house would be willing to live in it.*" Even in applications where 3DCP holds a clear advantage, it is difficult to create a 'side-by-side' comparison. This is because 3DCP uses completely different design principles, requires operators with different skills, and is subject to different quality control and maintenance plans. Even though 3DCP structures were more expensive, the performance benefits in terms of, for instance, comfort and thermal efficiency, would outweigh those costs. However, right now there is a lack of tools to perform those cost-benefit analyses. With such uncertainty, and given that "*construction is simply very price driven,*" it is unlikely that construction firms will make large investments in an immature technology with no direct cost reduction, unless there is additional institutional support.

When interviewees were asked which factors contributed most to the cost of using 3DCP, and what were the most feasible ways to drive down costs, two factors stood out: material and quality control. "*The challenge is that the average cost of large construction is the low cost per kilogram … For a house, it is like 1 euro per kilogram, or even less.*" 3DCP materials are considerably more expensive than traditional concrete mixtures, for two reasons: there is not enough demand to scale-up production and achieve economies of scale; and there are few suppliers of 3DCP materials. In the absence of competition, material suppliers do not need to lower their prices. Furthermore, as there are few suppliers, materials have to be transported over longer distances, thus substantially increasing transportation costs and the environmental footprint of such transport.

Quality control represents an important share of the final cost, given the lack of standardized procedures for designing 3DCP structures. "*What Eurocodes has now is Design by Testing … we have to make a 1:1 prototype, test it, and based on that test we can 3D print it and get it certified as safe … This process is very expensive because you have to make a bridge or house twice.*" Once the final product has been built, non-destructive 'diagnostics testing' is then carried out. For instance, a bridge might be tested by putting on it the maximum load that the bridge design allows, and checking that the structure holds. Testing costs are supposed to go down, as researchers are creating digital twins to simulate the behavior of 3DCP structures, "*the more testing you do, the more efficient your digital twin becomes as you feed it more data … in the future, these digital twins will help to create building codes.*"

Furthermore, there are important concerns about the long-term behavior of materials. In some tenders, contractors need to ensure that a bridge will last 100 years. However, because 3DCP is so new, there is considerable uncertainty about whether 3DCP structures will fail in the future in unknown ways. This creates "*a lot of fear … If we have a bad experience, the rules [building codes] will be tightened again … People want to [innovate], but if at some point it becomes project-specific and you talk about it at project level, their overwhelming fear is the 100-year lifespan.*" Tightening the building codes would likely make 3DCP less attractive.

Despite the current economic challenges, 3DCP offers two attractive benefits to the managers we interviewed: reduced formwork costs, and increased consistency. "*The costs of formwork are [approximately] one-third of the total costs, the rest is proportionally cement and labor; in other words, formwork accounts for on average 50 percent of the material costs.*" This cost structure means that, even if 3DCP materials are more expensive than traditional materials, this might be compensated by the time and cost saved in creating the formwork and the manual labor to pour the concrete. An interviewee suggested that right now, the most promising applications are those "*where people are in danger, where you print very complex things, somewhere in between, under the ground, or in difficult spaces you cannot get to with trucks.*"

As with any other automated process, the variability of 3DCP is lower than using manual labor. "*A 3D printer does it right or does it wrong, but with people, they may be doing well today and things will go wrong tomorrow, and you are not in control.*" A company that knows how to use 3DCP to obtain the desired structural properties could therefore save substantial amounts of money on rework costs and failures. Reducing the risk of having to rebuild a certain component could outweigh the extra costs associated with 3DCP. "*We are talking about a profit margin of 2 to 3 percent, and we have a lot of failure costs. We have a lot of damage, which depresses the profit margin or reduces it to loss … If you are talking about risk, it is better to buy one prefab pile that is more expensive but is good, than three cheaper piles for which I have to make two afterwards.*" Reducing the need for rework would also reduce a project's environmental footprint, as less material is required.

4.4. Summary: balancing planet, people, and profit

Significantly, our analysis of how the industry perceives the opportunities and challenges with 3DCP (see sections 5.1 to 5.3) shows that, despite 3DCP's potential to substantially increase the sustainability of construction activities, early adopters face several trade-offs across the triple bottom line dimensions. Table 1 summarizes our findings, and highlights which 3DCP characteristics create tension between the planet, people, and profit. The horizontal rows show the main advantages of 3DCP, as claimed by its proponents (Alhumayani et al., 2020; Bos et al., 2016; Paolini et al., 2019), summarized in section 2. The columns represent the triple bottom line dimensions (Elkington, 2008).

Table 1
Adopting 3DCP presents numerous tradeoffs in terms of sustainability across the triple bottom line dimensions. Positive effects are shown as (+) and negative effects (−).

3DCP characteristic	Effect on planet	Effect on people	Effect on profit
Reduces material usage	+ Reduce concrete production and transportation's environmental footprint + No need to build formwork, which has a limited reuse capability - Even when its use is cut, concrete is still large and problematic. - Material supply for 3DCP is scarce and might need to be transported over longer distances	- No need for carpenters making formwork	+ Large potential savings in material costs and expenditures related to formwork - 3DCP materials are more expensive than conventional concrete - Alternative materials to concrete might be even more expensive
Design freedom to make complex geometries	+ Can improve energy efficiency and other performance parameters with a holistic design approach - Holistic designs can be less modular, and contradict circularity principles	+ Designs can be more easily tailored to individual user demand + Incentivizes the creation of highly-skilled jobs	- Integrated designs cannot be easily compared side-by-side with traditional designs, making it difficult to assess if 3DCP is cost-competitive
Automation	+ Higher quality control means less waste and fewer failures	+ Automation-related jobs are more stable, and better paid, than current migrant seasonal workers +/− If not enough construction workers in the future, automation would be only option - 3DCP requires less labor than conventional concrete pouring	+ Large savings related to failure costs. Lower variability reduces uncertainty for project managers - High expenditure needed in equipment, R&D, and quality control

5. Discussion

5.1. Strategic decisions affecting 3DCP sustainability

Our findings suggest that the sustainability-related benefits of 3DCP depend greatly on how a firm implements the technology. Given the current level of technical uncertainty, there is no clear adoption strategy. Consequently, companies appear to be approaching the technology cautiously. To guide managers in their decision-making, we discuss five key decisions for construction companies regarding 3DCP, and their implications for sustainability (see Table 1). These decisions are interdependent, and the optimal solution depends on each firm's short- and long-term strategic goals.

The first two intrinsically related decisions are whether or not to invest in 3D printing technologies, and if so, whether to use concrete as base material. Despite 3DCP's potential to both reduce the environmental impact of construction activities and increase structural performance, advanced robotic equipment requires large investments in R&D to gather the knowledge required to design and build robust structures. In addition, it is unclear whether concrete is a sustainable choice in the long term. Because companies are already familiar with concrete's properties, designing (safe) concrete structures with 3DCP should be easier than learning how to use other materials. The disadvantage of concrete is that there is currently no widespread procedure to reuse and recycle it. Despite multiple ongoing research programs to develop more environmentally-friendly material mixtures suitable for 3DCP (e.g. Panda et al., 2019), their properties and when they will be commercialized, are not clear. If, as some interviewees believe, it is necessary to abandon the use of concrete as soon as possible, 3DCP might only be delaying transition to the circular economy. Conversely, adopting 3DCP could help companies get acquainted with digital infrastructure and design principles for working with other materials. For instance, the MX3D bridge, installed in Amsterdam in 2018, is a 12-m long structure 3D printed in stainless steel (Gardner et al., 2020). This bridge benefited from the design freedom offered by 3D printing, without the negative environmental connotations of using concrete.

Once a company has decided to use 3DCP, three options determine the design process. One option is whether to design modular or integrated structures. Modular structures are believed to be more sustainable than integrated ones (Mignacca et al., 2020), as portions of the final structure requiring maintenance can be replaced without having to change the entire structure, thus reducing waste and increasing circularity (Nowak et al., 2018). However, modular structures require additional materials, as the interfaces between the different components introduce stress concentration points and therefore potential structural weaknesses. Yang et al. (2019) suggest that, from a sustainability perspective, deciding between modular or integrated designs should depend on 1) the potential for light weight; 2) the improvement in performance; and 3) the anticipated lifespan.

Companies need also to evaluate whether to 'make or buy' 3DCP components. Companies typically outsource part of their production if they lack the know-how to produce components, or there is low technological opportunism (McIvor, 2009). Conversely, companies tend to vertically integrate the production of components if the product complexity is high (Novak and Eppinger, 2001), or if it is considered a core capability and source of competitive advantage (Dekkers, 2000). Nowadays, companies outsource the production of 3DCP components to specialized suppliers. That said, if the technology evolves to the point of becoming a mainstream, rather than a niche construction technology, companies may find it advantageous to insource 3DCP activities. For metal 3D printing, General Electric decided to take over the companies Arcam and Concept Laser, two suppliers of 3D printing equipment (Rogers et al., 2018).

Finally, 3DCP adopters need to assess whether it is better to produce components on-site or off-site. On the one hand, producing components off-site might improve process control and part quality, key technical limitations in immature manufacturing technologies. However, off-site components need to be transported from the factory to the construction site. The need for transportation limits the maximum size of the components that can be printed. On the other hand, producing components on-site allows constructors to build larger structures right away, without the hassle of transportation. At the same time, printing on the construction site is less stable due to changing environmental conditions, and might be more prone to failure.

The decisions regarding modularization, outsourcing, and location are highly interdependent. Modular designs facilitate a more flexible supply chain (Davies and Joglekar, 2013), which in turn could foster competition among suppliers. If supplier competition drives down prices, then outsourcing might be cheaper than producing components in-house (Rossetti and Choi, 2005). If quality control is a priority, and companies prefer off-site production, modular design might be the only economically viable choice. Conversely, companies that are keen to exploit the performance benefits of 3DCP, for instance to reduce dependence on manual assembly, may prefer on-site 3DCP for large consolidated structures. In that case, 3DCP would become critical to their operations, and companies might prefer to insource 3DCP activities. The optimal strategy depends on each company's characteristics and how the technology is expected to evolve in the years to come.

5.2. Policy implications

In light of the great sociotechnical uncertainty surrounding 3DCP, it will probably not be adopted widespread unless institutional support lowers some of the adoption barriers. Based on our findings, three areas where policy support could help that transition are: regulation and standardization, experimentation and data sharing, and workforce development.

Governments and scholars advocate adopting 3DCP based on its potential environmental benefits (Alhumayani et al., 2020; Bos et al., 2016; Weng et al., 2020). However, our interviewees suggested that government tender requirements are nowadays too low to have the technology-forcing effect that regulation has had in other industries such as automotive (Lee et al., 2010). While industry members expect tender requirements to become increasingly stringent, in order to meet national and European long-term sustainability objectives, it is unclear how that transition will happen. Furthermore, current building codes mandate the use of Design by Testing methodologies, which substantially increase the cost of using 3DCP, and eliminate any potential material savings, as structures need to be duplicated in order to be tested.

To change building codes while ensuring public safety, large-scale testing of 3DCP structures is needed to create meaningful physical models which can replicate the material's behavior. Therefore public support might be required on two fronts: first, for funding pilot programs to lower the high uncertainty surrounding 3DCP's structural behavior and economic feasibility. Pilot projects should have an accompanying long-term monitoring plan, to ensure any unforeseen flaws in 3DCP structures are detected early, and remedied before they cause the public any harm. In the absence of these measures, current sociotechnical uncertainty about 3DCP is incompatible with risk management practices in building design, which are generally conservative and risk-averse. Second, public support might be needed for establishing public-private partnerships in order to create repositories for collecting and analyzing experimental material data from laboratories and real-life projects. While high-quality material data is vital for designers to optimize structures, it is unlikely that a single firm would have the resources to create such a repository. Based on similar experiences with metal 3D printing (Bonnín Roca et al., 2016), we anticipate that getting reluctant material suppliers to share the composition of their mixtures will be quite a challenge. To overcome this problem, public agencies could set up standardization committees (Wiegmann et al., 2017) to foster the homogenization and characterization of 3DCP mixtures.

The construction industry is facing a global shortage of skilled labor, reported in the literature in diverse countries such as Australia (McGrath-Champ et al., 2011), the United Kingdom (Nadim and Goulding, 2010), and China (Ho, 2016). 3DCP is likely to add more pressure to the existing shortage. On the one hand, designing for 3DCP requires a new generation of designers who know how to exploit the technology's advantages to the full. On the other hand, R&D engineers and operators have to establish a robust construction process which limits variability in the quality of the printed components, and troubleshoot any potential incidents during the printing process. Right now, there are no comprehensive training programs for 3DCP and most knowledge is tacit. An option would be to extend existing training programs for 3D printing to other materials, such as polymers or metals. However, the mechanical properties of concrete, and the size of the components printed, vary greatly between 3DCP and other 3D printing applications. At this time, it is unclear which components of existing training programs could be re-used, and which components need to be developed specifically for the construction sector.

6. Conclusion and future research

It is early days for 3DCP, and many questions about its long-term sustainability remain answered. In terms of environmental sustainability, comprehensive life-cycle assessments are required to evaluate the real environmental impact of raw material production for 3DCP. It is still highly uncertain to what extent alternative material mixtures could reduce that impact. Future research needs also to assess how design choices, such as the degree of modularity introduced in 3DCP structures, affect both concrete's potential to achieve circularity, and a structure's performance parameters.

From a social sustainability perspective, our study contributes to current debates on skill-biased technological change (Card and DiNardo, 2002), and technological unemployment (Kim et al., 2017). While our findings suggest that adopting 3DCP would reduce the need for low-skilled labor, the construction sector is also facing a labor shortage and relies on a supply of seasonal workers who do not enjoy the opportunities 'to prosper and flourish' (Missimer et al., 2017). Given that the construction sector is an important work source in many countries, a shift towards automation could have deep structural consequences. Future work could provide insight on the number of jobs affected by higher levels of automation in construction, and equally the balance between the number and quality of jobs.

At the moment, managers at construction companies do not have adequate decision tools to evaluate the cost-competitiveness of 3DCP against other technological alternatives. Future work is needed to create comprehensive techno-economic models that take into account not only the costs associated with 3DCP production, but also aspects relating to quality, labor, and maintenance. As there is not a large enough market for 3DCP materials and equipment, and the technology is evolving rapidly, forecasting techniques will be needed to anticipate the impact of technological change on 3DCP costs. Researchers could, for instance, study the historical evolution of costs in prefabricated construction, or of 3D printing in other industries, to gain insights about how industry- and firm-level learning rates impact costs.

CRediT authorship contribution statement

Max Adaloudis: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Jaime Bonnin Roca:** Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Validation, Visualization, Supervision, Resources, Writing – review & editing.

Declaration of competing interest

The 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. List of interviewees, in chronological order

Position	Organizational background	Duration of interview (minutes)
CEO & Co-founder	Supplier 3DCP equipment (1)	55
CEO & Founder	3D Printing architectural company	96
Researcher, structural design	Academia	75
Sustainability manager	Focus firm	87
Independent consultant, specialized in concrete	Academia & freelancer	47
Former innovation manager	Focus firm	47
Innovation manager	Focus firm	76
Business developer, emerging technologies	Consulting	47
Tenders manager	Focus firm	45
Design and testing consultant	Several construction companies	47
Project leader	Focus firm	46
Design and testing consultant	Focus firm	60
Sustainability project advisor	Focus firm	59
Senior procurement and materials manager	Focus firm	50
Asset management	Focus firm	34
Researcher, 3DCP process development	Academia	60
Business development & innovation	Focus firm	54
Business intelligence	Focus firm	31
CEO	Supplier of 3DCP equipment (2)	60
Sustainability manager involved in 3DCP project	Government	45

Appendix B. Interview sample questions

Set 1: Questions related to technology.

- What do you think are the main advantages and drawbacks of 3DCP?
- What are the limitations of 3CDP in terms of structural integrity and material variability?
- To what extent is 3CDP limited by regulations and building codes?
- How can 3CDP be integrated with traditional construction techniques?
- In which applications do you see the largest potential for 3DCP to increase productivity?

Set 2: Questions related to environmental sustainability.

- What is the potential of 3CDP in terms of material savings? To what extent can geometries be optimized?
- Do you see 3DCP as a viable way of achieving current sustainability goals in construction?
- What are the perspectives on re-using and recycling concrete?
- How do potential environmental benefits compare to a potentially higher cost?
- To what extent does the use of MKI scores incentivize the adoption of young technologies?

Set 3: Questions related to social sustainability.

- What do you think might be the impact of 3CDP on the labor market?
- What could be the impact of 3DCP on construction workers' safety?
- What are the training needs in the construction sector to use 3DCP?
- In what ways can 3DCP be applied to enhance users' experience of the built environment?
- To what extent is the aesthetics/design factor considered in tenders?

Set 4: Questions related to economic sustainability.

- How do the costs of using 3DCP compare with traditional construction?
- What are the potential financial gains of automation?
- Do you think 3DCP might save time?
- How does the tendering process affect the chances of adopting 3DCP?
- What are the tradeoffs using 3DCP on-site versus off-site (prefabricated)?

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