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Designing for disruption: Exploring how digital technologies affect the future of construction

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This thesis explores how digital technologies may disrupt the construction sector. It builds on four interconnected studies: A) A horizon scanning that identifies 133 potentially disruptive technologies. B) A literature-based analysis revealing to which extent disruption theory applies to a construction sector context. C) The identification of three future visions for a digitally transformed construction sector, based on interviews with 13 innovation-savvy construction professionals. D) The development of a design game, called the Technology Cards, which facilitates future-oriented, strategic dialogues on the potential of 22 selected technologies.

Synthesising the four studies, the thesis proposes that construction companies benefit from applying inclusive, long-term-oriented foresight methods to prepare for disruptive change. The thesis provides recommendations for established construction companies to realise the emerging benefits of digital technologies, hereby enabling a democratic and deliberate digital transformation of construction.

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Designing for Disruption: Exploring how digital technologies affect the future of construction

DTU Management
PhD thesis

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Designing for disruption

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December 21, 2020

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By
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Preface and acknowledgements

In 2017, when I began this PhD, the name of disruption was on everyone's lips. The notion of disruption was used to create a sense of urgency across all sectors of society. The Danish government even established a Disruption Committee, appointing 32 prominent industry representatives to investigate how the Danish nation could insure itself for the future. Since then, the hype of disruption has declined. Nevertheless, the main message of disruption persists: The future will be radically different from the present, and proactive measures are needed to prepare.

The notion of disruption also motivated this PhD. The construction consultancy NIRAS A/S contacted the Technical University of Denmark for advice on how they should respond to the many emerging, and potentially disruptive, digital technologies entering construction. At the same time, I was looking for a new problem to dive into, and I found that digitalisation of the construction sector represented such a new inspiring problem. I have always been interested in unravelling complex challenges, and I think it is safe to say that in this PhD project, I found lots. In retrospect, committing to write a PhD which essentially asks: "How will the future look like?" appear to be a bad idea. No matter what I would find, no one could know if I was wrong or right, before many years from now. I cannot say for certain that a given technology is disruptive, predict the future potential of digitalisation or prescribe how disruption can for sure be avoided. But nevertheless, along the way, I made peace with all these uncertainties. I found that, even though we cannot validate a set of findings, we should not consider them invalid. That even though we cannot know the future, we should not stop envisioning it. And that, when no one knows anything for sure, the little we do know become quite valuable.

I would like to express my sincere gratitude to my two superb supervisors, Professor Anja Maier and Associate professor Christian Thuesen, who have guided me and believed in me on the way. Looking through my notes from three years of bi-weekly supervisor meetings, I find that your commitment and consistent guidance have steered me safely through the swamp of questions with no answers. Anja, thanks to your passion for design research and eye for details, I have come closer to understanding my academic standpoint as a design and innovation scholar. And Christian, thanks to your passion for construction research, and great ability to challenge my points of view, I have learned a lot and come to appreciate the intricacies of construction management.

At NIRAS, I would like to express my gratitude to several key persons. My manager through four years, Laurids Rolighed Larsen, who with his peaceful character, showed interest in my project and believed in me on the way. Christian Mossing and Stig Brinck, who with enthusiasm and success, marketed the *Technology Cards* and pushed the digitalisation agenda even further. Josefine Christensen, whose eye for graphic design has ensured that the Technology Cards as well as the figures in this thesis shine. And Carsten Heine Lund and Mads Søndergaard, who made this project a reality and followed its progress with interest.

As an industrial PhD student, I have been lucky to have great colleagues in two workplaces. I would like to thank my wonderful colleagues at NIRAS' Business Unit for Data, Analytics & Planning, and at the Technical University of Denmark, Engineering Systems Design Section. I would also like to thank the master students Maj Riber Gunvid and Joanna Nathan Jensen for helping me explore the potential of the initial versions of the *Technology Cards*. Moreover, I would like to thank Professor Jennifer Whyte and her team of researchers at Imperial College London, as well as Professor Bock and his team of researchers at Technische Universität München, for hosting me at my research stays abroad.

The industrial PhD project was funded by Innovation Fund Denmark and NIRAS A/S. Additional funding was provided by Boligfonden Kuben. I would like to thank all three contributors for their financial support and interest in my research. Moreover, I would like to thank all the interviewees and workshop participants, who anonymously contributed to this research by providing empirical depth.

Finally, I would like to thank my wonderful family. Thanks to my mom and dad, whose love and support I have never doubted. And a heartfelt thanks to my dear husband Anders, for always believing in me, inspiring me and for taking care of the kids, while I was running the last mile to the finishing line. Your love and support keeps me going.

Blovstrød, December 2020

Sidsel Katrine Nymark Ernstsen
MSc.Eng. in Design & Innovation

Summary

Rapid technological developments change our ways of collaborating, communicating, producing, and doing business across a large number of sectors. New technologies, such as robots, internet of things, virtual reality, 3D printing and artificial intelligence, break down the barriers between industries, change market landscapes and disrupt established companies.

This thesis studies one of the least digital sectors of society, namely the construction sector (Gandhi et al. 2016). The construction sector is large and societally important, offering schools, hospitals, offices, railway, roads and more. Although the sector has great improvement potential, it struggles to implement digital technologies and obtain productivity improvements in a scale that are comparable to those of other sectors (Barbosa et al. 2017; Lavikka et al. 2018; Winch 2003a; World Economic Forum 2016).

This thesis applies the lens of disruption theory (Christensen 1997; Gans 2016a) to explore how digital technologies may affect the construction sector in the future. The thesis builds on four distinct, yet interconnected, studies:

- In the Disruption Paper (Ernstsen et al. 2018a), we dive into disruption literature and strive to answer three questions: Why should construction be ripe for disruption? When will disruption potentially occur? How will disruption likely manifest? By comparing construction to healthcare (another large and societally important sector that is considered ripe for disruption), we discuss limitations and benefits of using disruption theory to anticipate future changes in the construction sector.

- In the Horizon Scan Paper (Ernstsen et al. 2018b), we use a specific foresight method, horizon scanning, to identify 133 emerging technologies from across sectors. We find that the majority of these technologies are digital and that few focus on construction applications.

- In the Vision Paper (Ernstsen et al. 2021), we investigate how innovation champions of the construction sector envision the future of the sector. Through qualitative interviews with 13 construction professionals in the UK, we identify three visions for the future of the sector, which we name *efficient construction*, *user-data-driven built environment*, and *value-driven computational design*. The three visions highlight the potential of different technologies and trends and may be used as a frame of reference in strategic dialogues that explore multiple, possible, digital futures of construction.

- In the Technology Cards Paper (Ernstsen et al. n.d., under review) we present a design game that we developed, which can help business managers grasp the potential implications of digitalisation. The game is called the *Technology Cards*, and is a deck of cards that presents 22 technologies of importance to the construction sector. The design game was validated by means of 17 *Tech Session* workshops with 257 participants, revealing that the cards provide an inclusive approach for engaging multiple stakeholders in strategic dialogues on technology-enhanced futures.

Synthesising the four studies, the thesis

- explores the applicability of disruption theory to a construction context,
- identifies a list of potentially disruptive technologies,
- envisions how digitalisation may affect the future of construction, and
- provides recommendations for established companies to navigate in digital futures.

The thesis highlights the importance of engaging multiple stakeholders in envisioning the future and argues that our (often unspoken) ideas of the future affect our present-day strategic choices. Moreover, the thesis emphasises the importance of considering the implications of a combination of multiple technologies rather than applying a single-technology perspective on digitalisation. The thesis proposes that the *Technology Cards* design game can help stakeholders, such as business managers, engage in future-oriented dialogues about the disruptive potential of digital technologies.

Resumé (dansk)

Den hurtige teknologiske udvikling påvirker hele samfundet, idet den ændrer vores måde at samarbejde, kommunikere, producere og drive forretning på. Nye teknologier som f.eks. robotter, internet of things, virtual reality, 3D-print og kunstig intelligens nedbryder brancheskel, ændrer hele markedslandskaber og foranlediger disruption.

Denne afhandling studerer en af de mindst digitale brancher i samfundet, nemlig bygge- og anlægsbranchen (Gandhi et al. 2016). Bygge- og anlægsbranchen er stor og samfundsmæssig vigtig, idet den står for at levere skoler, hospitaler, kontorer, jernbane, veje og meget mere. Selvom branchen har et stort forbedringspotentiale, kæmper den med at implementere digitale teknologier og opnå produktivitetsforbedringer i en skala, der er sammenlignelig med andre brancher (Barbosa et al. 2017; Lavikka et al. 2018; Winch 2003a; World Economic Forum 2016).

Denne afhandling anvender forskningsbaseret teori om disruption (Christensen 1997; Gans 2016a) til at undersøge, hvordan digitale teknologier kan forventes at påvirke bygge- og anlægsbranchen i fremtiden. Afhandlingen bygger på fire studier, der er dokumenteret i fire artikler:

- I den første artikel – the Disruption Paper (Ernstsen et al. 2018a) – fordyber vi os i teorien bag begrebet disruption, idet vi besvarer tre spørgsmål: Hvorfor forventes det at bygge- og anlægsbranchen bliver disruptet? Hvornår kan vi forvente disruption? Og hvordan kan vi forvente at disruption udfolder sig i praksis? Artiklen sammenligner bygge- og anlægsbranchen med sundhedssektoren (en anden stor og samfundsmæssig vigtig sektor, der forventes disruptet) og diskuterer fordele og ulemper ved at bruge disruptionsteori til at foregribe fremtidige forandringer i byggeriet.

- I den anden artikel – the Horizon Scan Paper (Ernstsen et al. 2018b) – bruger vi fremsynsmetoden ’horizon scanning’ til at identificere 133 nye teknologier på tværs af sektorer. Vi finder ud af at størstedelen af de identificerede teknologier er digitale, og at kun ganske få er tiltænkt bygge- og anlægsbranchen.

- I den tredje artikel – the Vision Paper (Ernstsen et al. 2021) – undersøger vi hvordan bygge- og anlægsbranchens såkaldte ’innovation champions’ forestiller sig branchens fremtid. Gennem kvalitative interviews med 13 innovationsinteresserede fagpersoner fra Storbritanniens bygge- og anlægsbranche, identificerer vi tre digitale visioner for branchens fremtid. Vi navngiver de tre visioner ’effektivt byggeri’, ’det bruger-datadrevne byggede miljø’ og ’værdidrevet, computer-baseret design’. De tre visioner fremhæver potentialet af forskellige teknologier og tendenser, og foreslås anvendt som referenceramme i strategiske dialoger, der udforsker byggeriets fremtid.

- I den fjerde artikel – the Technology Cards Paper (Ernstsen et al. n.d., under review) – præsenterer vi et designspil, som vi har udviklet til at hjælpe forretningsledere med at forstå de afledte effekter af digitalisering. Spillet er et kortspil, der hedder *Technology Cards* og præsenterer 22 teknologier, der er vigtige for bygge- og anlægsbranchen.

Spillet blev valideret gennem 17 *Tech Session*-workshops med i alt 257 deltagere. Vi konkluderer at kortene tilbyder en inkluderende måde engagere flere interessenter i strategiske dialoger om, hvordan digital teknologier vil påvirke vores fremtid.

Afhandlingen, der syntetiserer de fire studier, undersøger

- i hvilket omfang disruptionsteori kan bruges til at beskrive forestående forandringer i byggeriet
- identificerer en række potentielt disruptive teknologier
- forestiller sig hvordan digitalisering kan påvirke fremtidens byggeri
- giver anbefalinger til etablerede byggevirksomheder, så de bedre kan navigere i digitaliseringens muligheder.

I afhandlingen fremhæver jeg vigtigheden af at involvere mange interessenter i fremsynsprocesser, og gør opmærksom på, at vores (ofte usagte) idéer om fremtiden påvirker vores strategiske beslutninger her og nu. I forhold til digitalisering, understreger jeg vigtigheden af at overveje synergieffekterne mellem flere teknologier frem for at fokusere på potentialet af enkelt-teknologier. Derudover foreslår jeg, at *Technology Cards* designspillet kan hjælpe interessenter, såsom forretningsledere, med at konkretisere digitalisering, idet kortene kan bruges til at facilitere fremtidsorienterede dialoger om det disruptive potentiale af digitale teknologier.

Publications included in the thesis

Peer-reviewed conference papers
*Ernstsen, S. K., Maier, A., Larsen, L. R., and Thuesen, C. (2018a). “Is construction ripe for disruption?” *Association of Researchers in Construction Management (ARCOM) - Proceedings of the 34th Annual Conference*.

Ernstsen, S., Thuesen, C., Larsen, L., and Maier, A. (2018b). “Identifying Disruptive Technologies: Horizon Scanning in the Early Stages of Design.” *Proceedings of the 15th International Design Conference, DESIGN*, 1833–1844.

Journal papers
Ernstsen, S. K., Whyte, J., Thuesen, C., and Maier, A. (2021). “How Innovation Champions Frame the Future: Three Visions for Digital Transformation of Construction.” *Journal of Construction Engineering and Management*, 147(2016)

Ernstsen, S. K. N., Thuesen, C., Mossing, C., Brinck, S., & Maier, A. (*under review*). Technology Cards: A design game for navigating in a future of digital technologies. International Journal of Design.

*awarded the Paul Townsend Commemorative Award

Other publications

Peer-reviewed conference papers

Berg, J. B., Thuesen, C., Ernstsen, S. K., and Jensen, P. A. (2019). “Constructing archetypes: mapping business models in the construction value chain.” *Association of Researchers in Construction Management (ARCOM) - Proceedings of the 35th Annual Conference.*, Leeds, 397–406.

Ernstsen, S. K., Koch-Ørvad, N. ;, Berg, J. B., Brinck, S., Thuesen, C. ;, and Maier, A. ; (2018c). “Learning from Digitalised Industries: Designing Value Propositions for Disruption.” *Proceedings of the 29th ISPIM Innovation Conference*, Stockholm.

Willumsen, P. L., Oehmen, J., and Ernstsen, S. K. (2018). “Reconceptualizing design risk management as a learning strategy.” *Proceedings of the 15th International Design Conference, DESIGN*, 2529–2540.

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Malmgreen, H. (2019). “Nyt projekt kortlægger byggebranchens digitale fremtid.” Jyllands-Posten, <https://jyllands-posten.dk/jperhverv/ECE11448074/nyt-projekt-kortlaegger-byggebranchens-digitale-fremtid/> (Dec. 19, 2020).

“Spillekort inspirerer til digital udvikling i byggeriet .” (2019). Dagens Byggeri, <http://www.dagensbyggeri.dk/artikel/106253-spillekort-inspirerer-til-digital-udvikling-i-byggeriet? > (Dec. 19, 2020).

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1. Introduction

“Disrupt or be disrupted” has today become a well-known catchphrase by business managers: “Act now or your business may be lost”. That is the sense of urgency, business managers tend to experience when they speak of disruption. In the last two decades, several well-established companies have failed and lost great market shares in the favour of new innovations – and simultaneously, the notion of disruption has become extremely popular (Christensen et al. 2015). Across industry sectors, business managers acknowledge the need for creating innovative change to remain competitive.

In the construction sector, large-scale disruption has still not occurred. Buildings and physical infrastructure is designed, built and operated in a way that is largely similar to what it was 100 years ago (Winch 1998). However, now the winds of change are blowing in construction. New technologies such as robots, internet of things, virtual reality, 3D printing and artificial intelligence are beginning to show their worth in the construction sector (World Economic Forum 2016). Is it a sign of disruption approaching? And, in that case, what should construction companies do?

In this thesis, I unfold how new technologies may affect the construction sector and outline how established construction companies can prepare for a future of possible disruption. Reviewing literature, I identify a research gap, exploring whether disruption principles apply to a systemic industry such as construction. I take steps towards filling this gap by applying a future-oriented design approach. I argue that construction companies need to engage in strategic dialogues on how a combination of multiple technologies will affect the long-term future, and propose a design game, the *Technology Cards*, that may aid companies in this activity.

1.1 Problem domain: Digital technologies entering construction

1.1.1 The power of digital technologies

Technology development is an important driver of change in our society. The invention of cars changed the way we transport ourselves, the invention of washing machines and other household appliances led to an increase in women entering the labour market, and the invention of the internet has enabled people from all over the world to communicate and interact. The implications of technological developments affect all parts of society.

One especially important invention is that of the computer. The computer introduced the revolutionising principles of digitising – i.e. converting analogue signals into digital signals and storing them as binary digits (Tilson et al. 2010). Digitising turned out to be a very powerful process, as it allows for information to be stored, processed and transmitted in a generic fashion, detached from physical assets. The lack of physical assets also makes digital solutions less constrained by the typical sectorial boundaries. As explained by Tilson et al. (2010)

> *"digitizing has the potential to remove the tight couplings between information types and their storage, transmission, and processing technologies—potentially shattering the dominant service model and the stability of the industrial organization"* (Tilson et al. 2010 p. 749)

In other words, as digital technologies develop, the barriers between traditional sectors break.

Digitalisation is the sociotechnical process of applying digitising principles to societal contexts (Tilson et al. 2010). The power of digitalisation affects all parts of society. However, the levels of digitalisation still differ significantly across sectors. Gandhi et al. (2016) found that sectors like IT, media, professional services and finance and insurance scored very high on digital advancement, while sectors like agriculture and hunting, and construction scored very low on digitalisation. Analysts expect that, in the coming years, this digitalisation gap will disappear as the traditional sectors begin to reap the benefits of digital technologies (Roland Berger 2015)

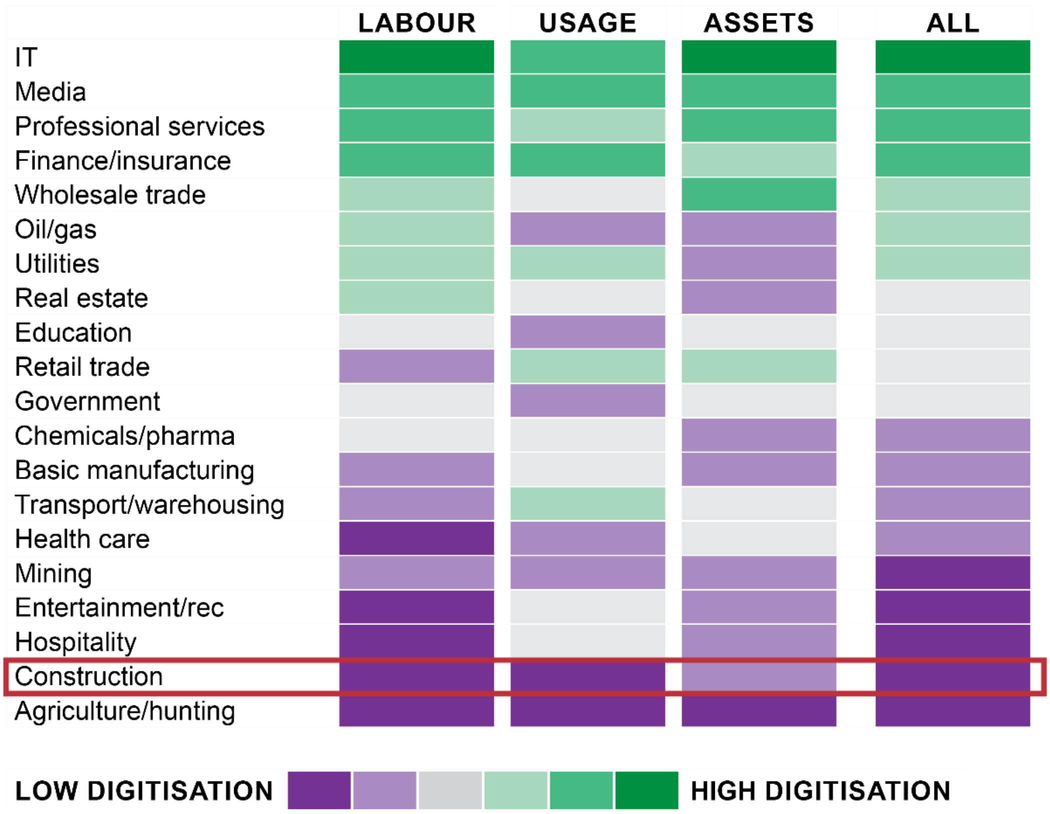

Figure 1: The level of digitalisation across sectors (adapted from Gandhi et al. 2016)

1.1.2 The construction sector struggling to benefit from digitalisation

As can be seen in Figure 1, one of the least digital sectors in society is construction. The construction sector is concerned with designing, building and operating built structures such as schools, hospitals, offices, railways and roads. The sector is of great societal importance and constitutes 9 % of the EU's gross domestic product (European Commission 2016). Construction products such as buildings and infrastructure are brought into existence as the result of contracted project-organisations with numerous stakeholders involved. Despite highly customised products, price is often one of the most important sales parameters in construction. As a result of a highly price-competitive market, construction companies typically operate on small profit margins and focus on ensuring short-term profitability rather than investing long-term in (risky) new technology (Bygballe and Ingemansson 2014).

Digital technologies are expected to affect the entire value chain of construction. Digital technology such as Building Information Modelling (BIM) enables the construction sector to switch from paper drawings to 3D and eventually 4D, 5D and 6D models of building data. This switch further enables the introduction of other digital technologies in the construction process, such as virtual reality to involve users in construction design, robots to assemble elements on the construction site, or artificial intelligence to optimise energy consumption once a newly built structure is in operation. Other technologies that might benefit construction include internet of things, 3D printing and generative design software. Observing the game-changing effects of digital technologies in other sectors, established construction companies wonder: what technological innovations should we invest in, why and how? Striving to find an answer to these questions, I draw on disruption theory.

1.2 Theoretical framing: Disruption as a phenomenon

A popular term for describing the game-changing effects of new technology is disruption. During the last two decades, many researchers and industry analysts have investigated the phenomenon of disruption (Christensen 1997; Christensen and Raynor 2003; Danneels 2004; Gans 2016a; Markides 2006; McKinsey & Company 2020). The notion of disruption is appealing as it describes why otherwise successful established companies fail, and how new competitors in a market can succeed.

The phenomenon of disruption occurs when established companies lose their market-leading position because a new entrant overtakes the mainstream customers (Christensen 1997; Gans 2016a). The new entrant – i.e. the disruptor – typically enters the market offering a technology-based product that initially offers a worse performance than the established products in the market (Christensen and Raynor 2003). However, as the technology improves, so does the performance of the disruptive product. As mainstream customers begin to prefer the disruptive product, established companies lose market shares, and disruption has occurred.

Few academic terms have gained as much traction as the concept of disruption. The original theory of disruption was built on a number of case studies in consumer-oriented, mass-production industries such as disk drives, mechanical excavators and retail stores (Christensen 1997). Over the years, the term has become popular and widely used to describe and prescribe company failure and success in almost any sector of society. However, it goes without saying that not all sectors of society are alike.

While many companies in the manufacturing sector use a make-to-forecast production strategy, most companies in the construction sector produce tailored solutions and apply the production strategies of concept-to-order or design-to-order (Winch 2003a). Moreover, the complexity of construction products and services make individual construction companies dependent on partners and suppliers, which affects their ability to implement innovation. As the theoretical concept of disruption builds on evidence from manufacturing sectors, it remains to be shown if and how disruption applies in a construction sector context. Acknowledging that industrial structures affect innovation dynamics, Christensen et al. (2018) issued a call for research on how disruption theory may inform – and be informed by – innovation strategies in systemic or network-based industries. This thesis strives to answer that call by framing construction as a complex systems industry (Winch 1998) and investigating how disruption may unfold in construction.

1.3 Research questions

When a market is disrupted, it undergoes tremendous change. Some of this change is positive: Products become better, processes become more efficient, customers become happier. Yet, when a market undergoes disruption, waste and losses also occur. Stores and offices close, employees are let go, well-liked products and traditions are lost. While disruption may be a positive change to a new entrant, the consequences of disruption can be devastating for established companies.

This thesis studies disruption from the viewpoint of existing construction companies. Correspondingly, the thesis focuses on how to *navigate in* disruptive changes – designing for disruption – rather than how to *create* disruptive changes. Moreover, it studies the potential consequences of disruption to the construction sector as a whole, rather than studying the consequences for specific construction companies or stakeholders.

The overarching research question of this PhD is:

RQ1: How might digital technologies disrupt the construction sector and what can established construction companies do about it?

To answer the first half of this overarching research question, I study the applicability of disruption theory and the anticipated impact of technologies on the future of construction. This is formulated in three sub-questions:

RQ2: How can theory-based perspectives on disruption aid construction companies in anticipating future change?

RQ3: Which technologies are potentially disruptive to construction?

RQ4: How might digitalisation affect the future of construction?

The activity of gazing into the future entails (qualified) guessing and estimations under a high degree of uncertainty. After all, there is no way to validate whether our current assumptions about the future correspond with what will happen. Correspondingly, this thesis does not aim to give an accurate account of the future – rather, it aims to make it easier for business managers and employees to navigate in an inevitably uncertain future.

To answer the second half of the overarching research question a fifth sub-question reads:

RQ5: How can established construction companies prepare for the potentially disruptive effects of new technologies?

This thesis is the result of a research collaboration between the Technical University of Denmark and the engineering consultancy NIRAS. Correspondingly, the knowledge and tool generated are envisaged to contribute to both research and practice.

1.4 Research approach: Design and futures studies

Studying the potentially disruptive impact of digital technologies entering the construction sector, I draw on methods and insights from the research fields of design and futures studies.

The field of design is relevant for several reasons: 1) When companies in the construction sector envision, commission, draw, build and optimise the operation of physical structures, they engage in a comprehensive design process. This design process is similar to other design processes, as it is multi-faceted, complex, dynamic and involve a large number of stakeholders (Dorst 2015). The field of design research is therefore relevant to construction contexts, and vice versa. 2) According to Dalsgaard (2017 p. 24), design is "*a field concerned with finding novel and useful ways of approaching and transforming uncertain situations in which there are no straightforward answers*." When construction companies seek to anticipate the impact of digital technologies on their sector, they are in a complex and uncertain situation and in need of novel and transformative solutions.

The field of futures studies is relevant, as I strive to anticipate the future impact of technologies on the construction sector. Futures studies are concerned with the identification and assessment of trends and the generation of possible, probable, and preferable futures (Kreibich et al. 2011). Futurists make use of foresight and forecasting methods, such as scenarios, Delphi, visioning and back-casting, and other interdisciplinary methods such as expert interviews, brainstorming, (futures) workshops, and morphology analyses (Popper 2008). The fields of futures studies and design intersect, as both fields are concerned with engaging stakeholders in analysing *what is*, projecting *what could be*, and synthesising *what shall be* (Ollenburg 2019). With this in mind, I frame this research as future-oriented design research.

1.5 Research structure

Structuring the research, I apply the Design Research Methodology (DRM) framework. This framework supports multi-disciplinary design research that aims to understand and improve a certain situation. The framework combines descriptive research, aimed at understanding a situation, with prescriptive research, aimed at improving the situation. In this thesis, the objective related to *understanding the situation* entails anticipating how digital technologies may be disruptive to a construction sector context. The second objective, which is related to *improving the situation,* entails developing support to improve established companies' ability to benefit from potentially disruptive technologies.

The research is structured by means of the DRM framework (see chapter 4.3). Motivated by the overarching research question (RQ1), the thesis reports on the findings from four separate studies (see Figure 2). The first three studies elucidate different facets of the problem domain by focusing on disruption, technologies, and futures, respectively. Collectively, these three studies constitute a comprehensive descriptive study I. The fourth study is a prescriptive study, as it entails the design of support for construction companies to navigating among potentially disruptive technologies

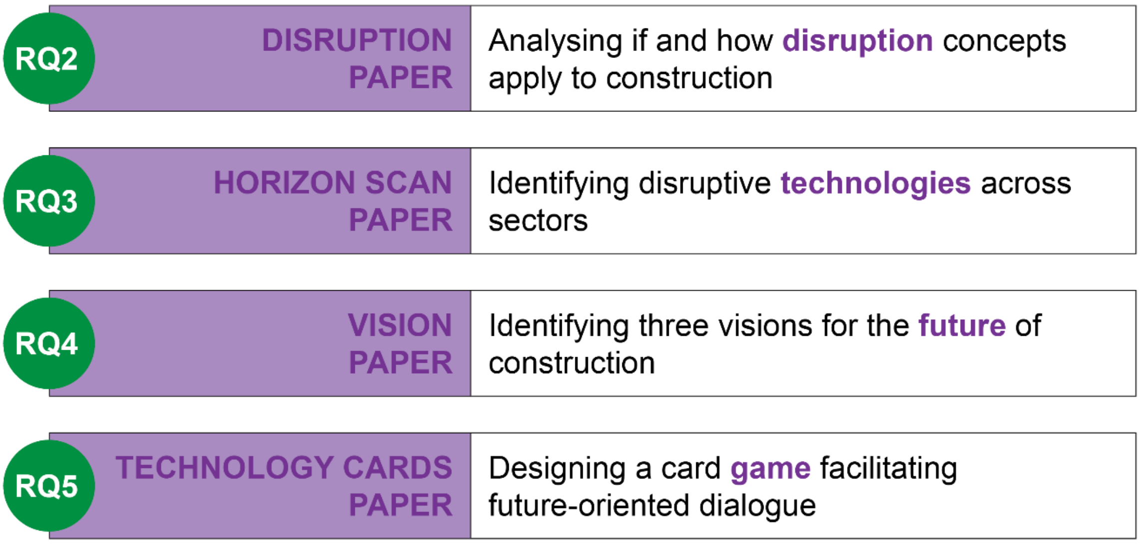

Figure 2: Four studies form the main body of this thesis

1.6 Research methods

The exploratory nature of the research questions guides the selection of research methods. To answer “why” and “how” questions, qualitative research data is useful, as it provides in-depth insights from multiple perspectives (Robson and McCartan 2016).

Research question 2 (RQ2) motivates the first paper “Is construction ripe for disruption?” (Ernstsen et al. 2018a). This paper is a literature-based study that compares the construction sector to another large and societally important sector claimed to be ‘ripe for disruption’, namely the healthcare sector. The comparative study identifies common characteristics of the two sectors, and discusses whether these characteristics are signs of approaching disruption. Furthermore, the paper applies four theoretical principles from disruption literature to a construction context and outlines several possible ways in which disruption may unfold in construction.

Research question 3 (RQ3) motivates the second paper “Identifying Disruptive Technologies: Horizon Scanning in the Early Stages of Design” (Ernstsen et al. 2018b). This paper applies the foresight method horizon scanning to identify potentially disruptive technologies across sectors. The horizon scan, which entails reviewing 11 reports and attending 9 conferences and seminars, results in a list of 133 – primarily digital – technologies. The paper validates this list of technologies by comparing it to the findings from 25 interviews with technology-interested stakeholders, and discusses the applicability of horizon scanning in a design context.

Research question 4 (RQ4) motivates the third paper “How Innovation Champions Frame the Future: Three Visions for Digital Transformation of Construction” (Ernstsen et al. 2021). This paper is an interview-based study that presents three visions for the future of construction.

Through qualitative coding of interview transcripts, the paper identifies 27 future aspects, that is, 27 technologies and trends that the interviewed construction professionals expect to affect the future of construction. By means of network analysis, the paper visualises how the future aspects cluster into three narrative visions for the future. The paper also connects the visions to current technology, business and policy discourses in the construction sector.

Research question 5 (RQ5) motivates the fourth paper “Technology Cards: A design game for navigating in a future of digital technologies” (Ernstsen et al. n.d., under review). This paper introduces a design game called the *Technology Cards*, and documents the iterative process of designing the cards by means of interviews, workshops and exhibitions. The *Technology Cards* are validated through 17 *Tech Session* workshops with 257 participants, demonstrating the relevance of using design games to facilitate constructive, future-oriented dialogues about new technology.

1.7 Research scope

This thesis centres around the notions of technology, construction and disruption. While each of these terms is defined in detail in chapter 2 and chapter 3, this section provides an overview of how I use each term to scope the research.

1.7.1 Construction

The construction process entails a large number of activities – from envisioning a new physical structure to realising it and optimising its operation. This process can be simplified as three main phases: design, construction and operation (Motawa et al. 1999). While I study the construction sector as a whole, I focus primarily on the construction design phase. Likewise, I focus on the challenges of established companies concerned with construction design activities, e.g., engineering consultancies, architects and contractors. See chapter 2.1. for more details.

This thesis draws on empirical studies conducted in Denmark and the UK, and the findings are therefore primarily relevant to this geographical area. However, as evident from international literature, the construction sector experience similar challenges with exploiting the benefits of new technologies all over the world (Barbosa et al. 2017; World Economic Forum 2016). Correspondingly, I argue that the findings of this thesis may be relevant to construction sectors on a global scale.

1.7.2 Technology

The notion of technology is multifaceted. In this thesis, I focus on technologies with some degree of novelty and game-changing potential. Furthermore, as this thesis aims to support construction practices, I will primarily focus on technologies that have been demonstrated applicable in a construction context. See chapter 2.2 for more details.

1.7.3 Disruption

The concept of disruption originates in studies of technological change and later evolved to study innovation and competitive response more broadly (Christensen et al. 2018).
I treat disruption as a phenomenon occurring as a result of new technology-based innovations entering a market (Gans 2016a). Rather than focusing on the intrinsic characteristics of disruptive technologies (Christensen 1997), or the market entrance strategies of disruptive innovations (Christensen and Raynor 2003), I focus on the implications of disruption to

established companies. To describe the technologies that can trigger disruption of a market, I use the term disruptive technologies. This term is not to be confused with Christensen's original concept of disruptive technologies, as I believe it is not the intrinsic characteristics of a technology that determines whether the technology ends up disrupting a market. Rather, I use the concept of disruptive technologies to describe technologies that possess the potential of acting as game-changers in the construction sector. See chapter 3.1 for more details.

1.8 Structure of the thesis

The thesis is structured as visualised in Figure 3. Chapter 2 introduces the empirical context of thesis by framing the construction sector as a complex systems industry, and describing the characteristics of digital technologies. Chapter 3 provides the theoretical framing of the thesis by introducing state-of-the-art literature on disruption, construction innovation and construction futures studies. Chapter 4 presents the thesis' future-oriented designerly approach to research and describes the selection of research methods. Chapter 5 summarises the four papers that form the main body of the thesis. Chapter 6 draws on the findings from these four papers, as it answers the five research questions and outlines implications for research and practice. Chapter 7 concludes.

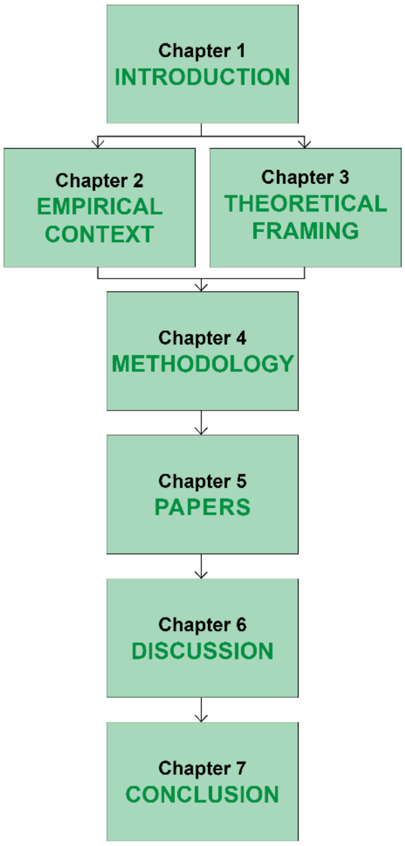

Figure 3: Structure of the thesis

1.9 Chapter summary

To introduce the thesis, this chapter:

- Presented digital technologies as powerful agents of change across all sectors of society.

- Outlined how the construction sector is struggling to realise the potential benefits of digitalisation.
- Introduced the theoretical notion of disruption and identified a research gap concerning the application of disruption theory to systemic industries, such as construction.
- Presented one overall research question and four supplementary research questions guiding the thesis.
- Argued for the relevance of applying a future-oriented design approach to study the potentially disruptive implications of digital technologies to construction.
- Introduced the Design Research Methodology as a framework for structuring the research.
- Presented the four papers that constitute the main body of this thesis and described the research methods applied in these papers.
- Scoped the thesis by giving a brief introduction to the terms of construction, technology and disruption.
- Outlined the structure of the thesis.

2. Empirical context: Digital technologies entering the construction sector

To obtain a more detailed understanding of the problem domain, this chapter introduces two central aspects of the thesis: Construction and technology.

2.1 The construction sector

Houses, schools, hospitals, offices, railways, roads, bridges, and airports; the products created and maintained by the construction sector are many. Scattered all over the world, the products of the construction sector contribute to our quality of life by providing shelter and enabling transportation. In other words, the products of the construction sector are vital to society.
This section introduces the problem domain of this thesis by outlining characteristics of the construction sector, framing it as a complex systems industry (Winch 1998), and describing key challenges of the sector.

2.1.1 Characteristics of construction

Construction is a very large sector, which constitutes 9 % of EU's gross domestic product (GDP) (European Commission 2016) and 13 % of the world's GDP (McKinsey & Company 2020). Moreover, the construction sector is a complex sector, which involves a large number of stakeholders and activities aimed at realising and operating physical structures (Harty 2008).

The main activities of the construction sector can be simplified into three main phases: design, construction and operation (Motawa et al. 1999). The first phase, design, involves all the activities that should be carried out before the first sod is cut on site – e.g. defining criteria, commissioning the project, drawing a solution, calculating costs and planning the construction. The second phase, construction, involves physical execution of the plans on site, e.g. excavation, pouring foundation, assembling structures, interior finishing, landscaping, and quality validation. The third phase, operation, involves planning and conducting maintenance, optimising energy consumption, carrying out modifications and repairs etc.

To create a definition that encompasses all of these activities of construction can be difficult. In this thesis, I draw on a definition by the UN, which considers construction to be:

> *"economic activity directed to the creation, renovation, repair or extension of fixed assets in the form of buildings, land improvements of an engineering nature, and other such engineering constructions as roads, bridges, dams and so forth."* (OECD 2013 p. 1)

In line with this definition, I consider the main product of construction to be buildings and infrastructure. Construction products, such as buildings, bridges, roads and railways, are typically tailored to the surroundings and need of the client. The bespoke nature of construction products entail that few construction products are alike, and that most construction products are complex. According to Miller et al. (1995), complex product systems embody three general characteristics:

- Many *interconnected,* and often customised, elements

- Continuously *emerging properties* and rising complexity through time, which means that small changes in one part of the product system can lead to large changes in other parts of the system.
- High degree of *buyer involvement* throughout the design and production of the system

Arguing that construction products are complex systems, Winch (1998) proposes that the construction sector can be considered a complex systems industry. The following section explains the implications of this framing, which is used throughout the thesis.

2.1.2 Construction as a complex systems industry

Complex systems industries are characterised by different groups of stakeholders that are highly collaborative, yet independent, and whose interests in innovation are partly competing (Miller et al. 1995). Some stakeholder groups (the innovation superstructure) represent the market for the complex systems, and other stakeholder groups (the innovation infrastructure) are necessary for the production of the complex system.

Figure 4 illustrates the actor network of construction by means of the complex systems industry model created by Miller et al. (1995) and adapted to construction by Winch (1998). This model highlights how the system integrator (i.e. the principal architect/engineer or the principal contractor) is essential to innovation in the sector, as this role connects the innovation superstructure (clients, regulators and professional institutions) to the innovation infrastructure (trade contractors, specialist consultants and component suppliers) (Miller et al. 1995; Winch 1998).

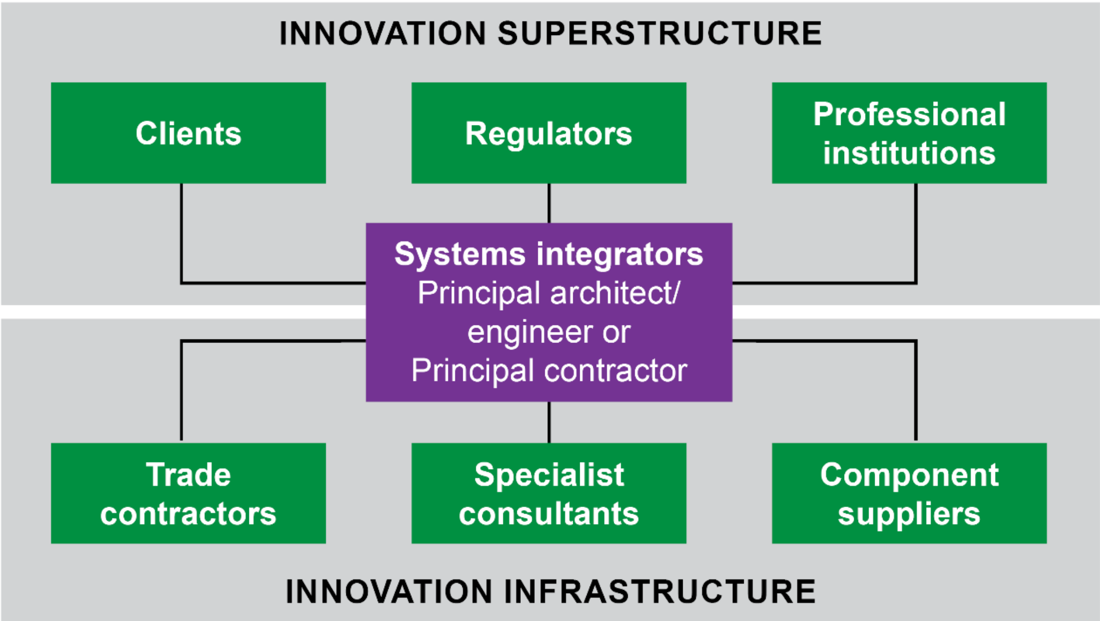

Figure 4: The construction sector is a complex systems industry. This model is adapted from Winch (1998), who adapted the original model by Miller et al. (1995) to a construction context.

The systems integrator plays a central role in coordinating between construction stakeholders and managing the changing needs and requirements to construction projects. Correspondingly, successful implementation of innovation in construction relies heavily on the capacity of the systems integrators to oversee and manage the system (Harty 2008). And correspondingly, this thesis studies innovation in construction from the point of view of established systems integrators.

In conventional models of innovation, one reads that a company designs a new product or service, which is then released for the customer to buy (Hobday 2000; Utterback and Abernathy 1975). However, this description of innovation does not apply to complex systems industries such as construction. Here, the design of a new product is negotiated with the customer, before the product is released. Therefore, I argue that the design phase is especially important, when studying innovation in complex systems industries. And correspondingly, this thesis focuses on the design phase of construction.

To sum up, I frame construction as a complex systems industry to emphasise how this sector is different from e.g., manufacturing, when it comes to innovation dynamics. This framing highlights the importance of the construction design phase and underlines the importance of systems integrators in driving sectoral change.

2.1.3 Key challenges of construction

Although construction is one of the largest sectors of society, it is neither the most digitalised nor the most productive sector. On the contrary, the sector struggles with improving productivity at a scale that is comparable to that of other sectors (Abdel-Wahab and Vogl 2011; Barbosa et al. 2017; Teicholz 2013). Industry analysists and researchers point towards several factors that inhibit change in the sector. One of these is fragmentation. Researchers describe three dimensions of fragmentation in construction:

- *Vertical fragmentation* occurs because different stakeholders are responsible for different phases of a construction project. Any innovation that affects several phases of a construction project needs to convince multiple stakeholders of the value of the innovation and gain their commitment to coordinated actions (Xue et al. 2014).
- *Horizontal fragmentation* occurs between companies working within a particular project phase. This kind of fragmentation is reinforced by the highly price-competitive bidding processes of construction (Hall et al. 2020). The price-competitive environment furthermore entails that construction companies harvest small profit margins and tend to invest in predictable innovations with a low risk profile (Bygballe and Ingemansson 2014).
- *Longitudinal fragmentation* occur because most construction innovation is carried out a project-level, rather than firm-level (Winch 1998). Construction projects are coalitions of companies and individuals that work together temporarily on a task before they split up and engage in a new project constellation. This makes it difficult to transfer learning from one project to the next, and hereby turn innovation into sustainable change (Blayse and Manley 2004; Thuesen 2007).

In addition to fragmentation challenges, industry analysts have identified several other root causes to the low productivity of construction (Barbosa et al. 2017; Molio 2020a). On an overall level, the construction sector is dominated by intense regulation and a cyclical demand structure, as the sector is highly dependent of public sector investments. On the interorganisational level, collaborations between various stakeholders in the sector is led by misaligned contractual structures, which do not sufficiently match risk and reward. And on a firm level, companies struggle with insufficiently skilled workers and a tendency to underinvest in innovation initiatives. All in all, the sector is caught in a deadlock, where change is difficult, and no change entails an increasing risk of disruption (Barbosa et al. 2017).

To support a digital transformation of the construction sector and enhance productivity, the World Economic Forum established a Shaping the Future of Construction project. This project has also published several reports that emphasises the disruptive potential of digitalisation and calls for immediate action (World Economic Forum 2016, 2018). Similarly, the consulting firm McKinsey has published several industry analysis reports highlighting the significant disruptive potential of digital technologies (Barbosa et al. 2017; McKinsey & Company 2020). This thesis builds on these reports, as it investigates how construction may leverage the disruptive potential of digital technologies.

2.2 Technology

To answer the research questions, and identify technologies that may be disruptive to construction, this section defines technology and present some important characteristics of technology in general and digital technology in particular.

2.2.1 Defining technology

Defining technology is not a straightforward task. The notion of technology can refer to an artefact (such as a computer), a creation process (such as 3D printing) or a human practice (such as science or culture) (Digironimo 2011; Kline 1985). Moreover, technology can be simple (such a ball bearing) or complex (such as the internet of things), and technology can be material (such as a printer) and immaterial (such as big data). To focus on the purpose of a technology, this thesis draws on a basic definition of technology proposed by Arthur (2009):

> *“a technology is* a means to fulfill a human purpose*. For some technologies – oil refining – the purpose is explicit. For others – the computer – the purpose may be hazy, multiple, and changing. As a means, a technology may be a method or process or device”*
> (Arthur 2009 p. 28 emphasis in original)

Most technologies consist of components or subsystems, which are in themselves also technologies (Arthur 2009). This adds complexity to the notion of technology, because technologies can be both generic, such as artificial intelligence, and specific, such as speech recognition software. To differentiate between these different levels of technology, Arthur (2009) uses the terms technology-plurals and individual technologies. Technology-plurals are umbrella terms for toolbox of components or a set of practices, whereas individual technologies – in line with the definition above – achieve a purpose.

2.2.2 The evolution of technology over time

A well-established pattern for describing the evolution of a technology is an S-curve (Cozzens et al. 2010) (see Figure 5). S-curves describe the rate of technological progress for an emerging technology: Initially the rate of progress is slow, but as the technology matures, the rate of progress increases. At some point, the technology fully matures and the rate of progress stagnates before it begins to decline. Typically, this is the point in time where a new technology emerges and, with it, a new S-curve emerges.

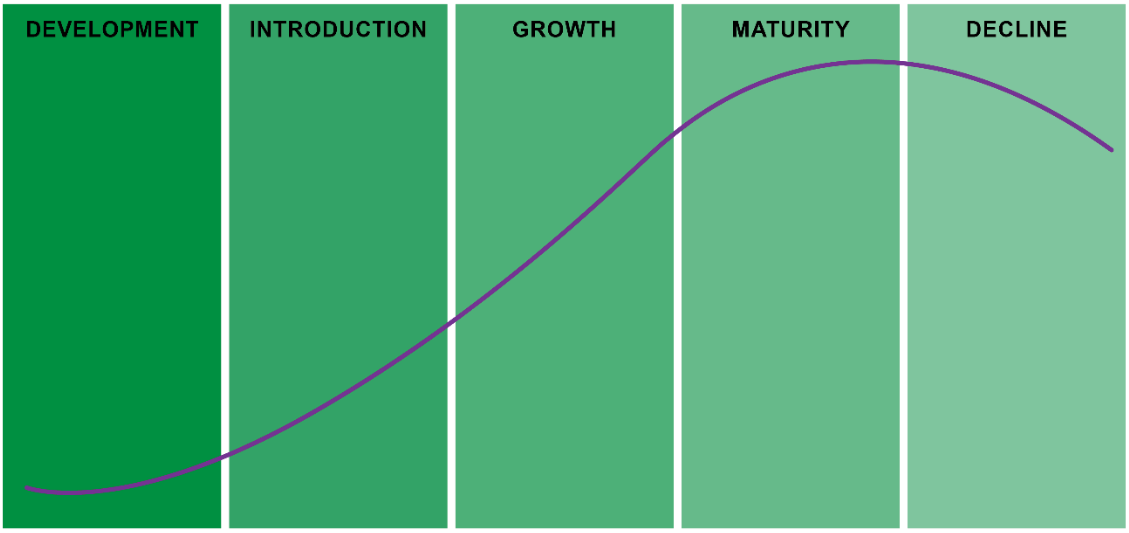

Figure 5: The evolution of a technology can be visualised by means of an S-curve. This model is adapted from Cozzens et al. (2010)

Building on the conceptual pattern of an S-curve, Phaal et al. (2011) propose a framework for industrial emergence (see Figure 6). This framework describes how a technology starts out as a science and transitions into a market-ready technology through several phases and milestones. One of these milestones is the *technology demonstration*, which occurs when a science demonstrates its feasibility and hereby transitions into a technology. The next key event, the *application demonstration*, occurs when a technology demonstrates its applicability in a specific market context. The following milestones include a *price-performance demonstration* and a *mass-market demonstration*, which occur as the technology proves to be commercially applicable in a mass market. As evident from the many demonstration events in initial phases of the framework, there is much uncertainty connected to early-stage development of a technology. While some technologies succeed, multiple other technologies fail to demonstrate their applicability in a mass market.

In this thesis, I strive to identify technologies that may disrupt construction. Correspondingly, I focus on non-mature technologies with a demonstrated application potential in a construction context, i.e. technologies that have passed the threshold of application demonstration. Moreover, I disregard mature technologies, which are fully implemented in the sector.

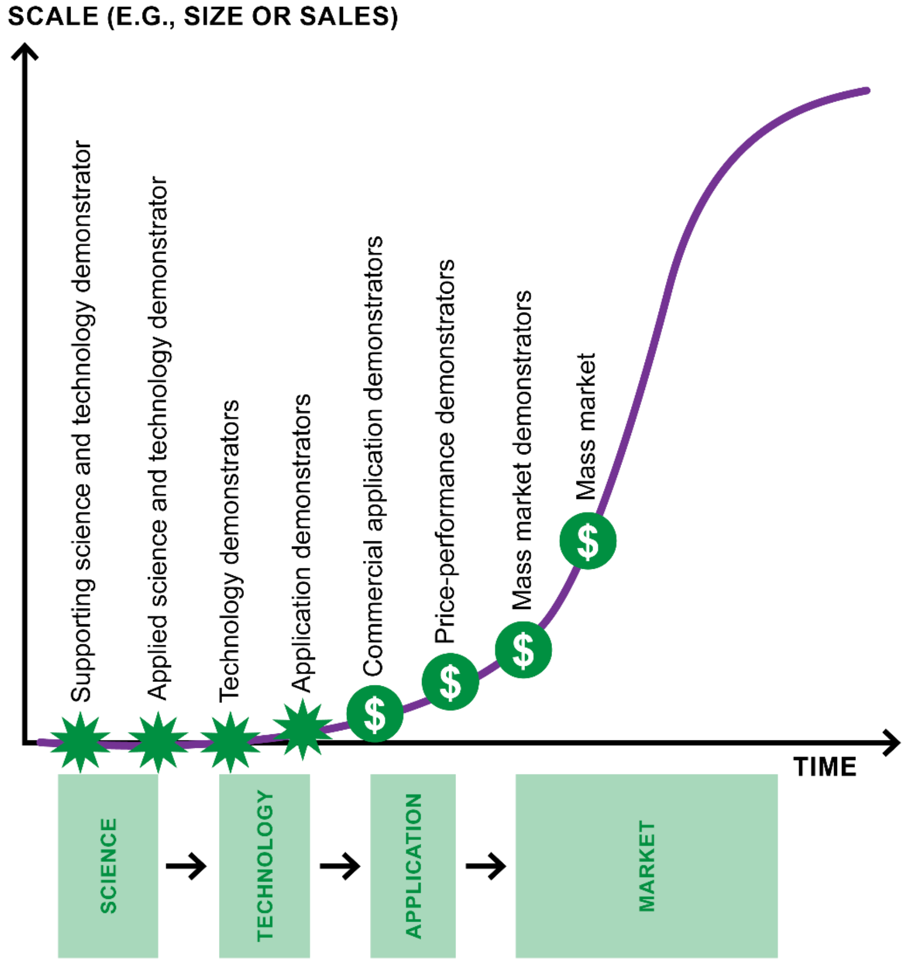

Figure 6: Milestones and phases of technology-intensive industrial emergence, adapted from Phaal et al. (2011)

2.2.3 Digital technologies

As described in the introduction, digital technologies are technologies that operate on the basis of digital signals, i.e. binary digits. Research suggest that digital technologies develop exponentially. In 1965, Moore observed how the number of transistors on integrated circuits doubled every two years, and he predicted that this growth rate would continue for at least ten years (Roser and Ritchie 2013). In other words, he predicted how technology capacity would increase exponentially in the years to come. Today, more than 50 years later, we find that Moore's law still holds true. Researchers have even shown how Moore's law apply to other technological performance parameters such as processing speed, memory capacity, and the size of pixels in digital cameras (Roser and Ritchie 2013). The exponential rate of change makes the implementation of digital technologies a difficult, but nevertheless important strategic activity in most businesses of today.

According to Woodhead et al. (2018), many construction companies use digital technology to improve what they do already, so it becomes faster, better, cheaper or safer. However, this single-technology implementation strategy is unfortunate as it risks to make data from one technology inaccessible to another (Woodhead et al. 2018). Moreover, the single-technology perspective does not trigger all the potential benefits of digitalisation. Large-scale technological change occur as individual technologies combine and recombine into new technologies (Parraguez et al. 2020). Considering the universal format of digital technologies, the potential for recombining technologies is arguably even larger than for traditional technologies. I therefore propose that to exploit the full benefits of digitalisation, companies need to apply a combinatorial perspective on the potential of digital technology. Correspondingly, this thesis explores how multiple, digital technologies affect the future of construction.

2.3 Chapter summary

Introducing the empirical context of this thesis, this chapter:

- Defined the construction sector and described how this sector differs from other sectors.
- Framed the construction sector as a complex systems industry (Winch 1998).
- Argued for why this thesis focuses on the role of systems integrators and concentrates on the design phase of construction projects.
- Presented some of the key challenges connected to realising the benefits of digital technologies in construction.
- Defined technology and described technology evolution by means of an S-curve (Cozzens et al. 2010).
- Described how technologies evolve from a science to a market-ready technology through four phases, while passing multiple milestones (Phaal et al. 2011).
- Scoped this thesis to focus on non-mature technologies, which have passed the 'application demonstrator' milestone.
- Described how digital technologies have triggered exponential rates of change that make technology implementation an important strategic activity.
- Argued for why a single-technology perspective is insufficient to realise the benefits of digital technologies, and scoped the thesis to focus on the combined impact of multiple technologies on the future of construction.

3. Theoretical framing: The game-changing effects of disruptive innovation

In this chapter, I give a state-of-the-art and theory-based introduction to disruption, construction innovation and construction futures, hereby providing the theoretical framing for the thesis.

3.1 Disruption

3.1.1 Different perspectives on disruption

Within the last 25 years, the notions of disruptive technologies, disruptive innovations and disruption have been heavily discussed among researchers and practitioners, and the terms are still subject to much scholarly discussion (Martínez-Vergara and Valls-Pasola 2020). Researchers have for example investigated how disruption should be defined (Danneels 2004; Fernendez et al. 2020; Markides 2006; Muller 2020; Nagy et al. 2016; Yu and Hang 2010), to what extent disruption can be quantitatively measured (Adner 2002; Govindarajan and Kopalle 2006; Guo et al. 2018), why incumbent companies fail to benefit from disruptive innovations (Macksey et al. 2018), and how incumbents should react to disruptive threats (Charitou and Markides 2003; Gans and Kaplan 2017).

While several definitions and points of view on disruption exist, the following sections will outline three well-established perspectives on the disruption phenomenon. These perspectives are summarised in Table 1. By approaching disruption from different points of view, I explore the advantages and drawbacks of each perspective of disruption. Christensen’s traditional notion of disruptive technology (Christensen 1997) is useful for early-stage, exploratory technology identification activities. In contrast, Christensen’s notion of disruptive innovation (Christensen and Raynor 2003) take away focus from the technological invention and focuses on the actual use of this invention. Finally, Gans’ perspective on disruption (Gans 2016a) is suitable for studying the effect of disruptive innovations on established companies. The following three sections describe the three perspectives in detail.

Table 1: Three perspectives on disruption

	DISRUPTIVE TECHNOLOGIES	DISRUPTIVE INNOVATION	DISRUPTION
Authors	Bower and Christensen (1995), Christensen (1997)	Christensen and Raynor (2003), Clayton Christensen Institute (2020)	Gans (2016a)
Main idea	Disruptive technologies bring to market a very different value proposition from what has previously been available. Typically, a disruptive technology is cheaper and of lower quality than mainstream alternatives.	Disruptive innovations enter the market from the fringe near the bottom of the market. Disruption occurs as the entrant persistently moves upwards in the market, eventually displacing the established companies.	Disruption occurs because successful companies continue to make the decisions that drove their success. Disruption can be explained by combining Christensen and Raynor's (2003) notion of disruptive innovation with Henderson and Clark's (1990) notion of architectural innovation.
Focus	Technology performance	Market entrance strategy of the disruptor	Decisions made by established companies
Categories	Sustaining vs. disruptive technologies	Low-end vs. new-market disruptive innovations	Demand-side vs. supply-side disruption

3.1.2 The classic view on disruption

Disruptive technologies

The notion of disruption goes back to 1995, when Bower and Christensen (1995) observed how certain technologies could cause well-managed, market leading companies to lose immense market shares. They argued that established companies fail because they stay too close to their existing, mainstream customers, while disruptive technologies enter the market and redefine what customers value. In 1997, Clayton Christensen elaborated on this phenomenon this in his classic book "The Innovator's Dilemma". Here, he defines that disruptive technologies "*bring to market a very different value proposition than had been available previously*." (Christensen 1997 p. xv). In contrast, sustaining technologies improve along the same parameters of performance that mainstream customers have historically valued. By means of examples from e.g. the disk-drive industry, Christensen illustrates how disruptive technologies can improve much faster than users' demand for the technology. Correspondingly, he advises established companies to focus on identifying disruptive technologies, invest in maturing them, and create an independent organisational unit to manage their development (Christensen 1997)

Disruptive innovation

In 2003, Christensen and Raynor replaced the term *disruptive technologies* with that of *disruptive innovations* (Christensen and Raynor 2003). Instead of focusing on the intrinsic characteristics of certain technologies, they reframed the theory to focus on the market entrance strategy of the disruptor. They argue that disruptive innovations originate in either *low-end* or *new-market* footholds. Low-end disruptors target customers in the least profitable end of the market with a low-price product that offers a worse performance than mainstream customers are used to. As the disruptive product improves (due to e.g. technological development), the disruptor takes over more and more of the mainstream customer segment and pushes the established companies to care only for the high-end customers (see Figure 7). In contrast, new-market disruptors create an entirely new market by targeting current non-consumers. Common for both strategies is that established companies tend to ignore the disruptor and only recognise the need for action, when it is too late. Studying examples of disruption, other researchers have found it difficult to distinguish between low-end and new-market approaches (e.g., Gans 2016a). In recent publications, Christensen also downplays the difference between the two terms, proposing instead that disruptive innovations target "*fringe customer groups, notably those near the bottom of the market*" (Christensen et al. 2018).

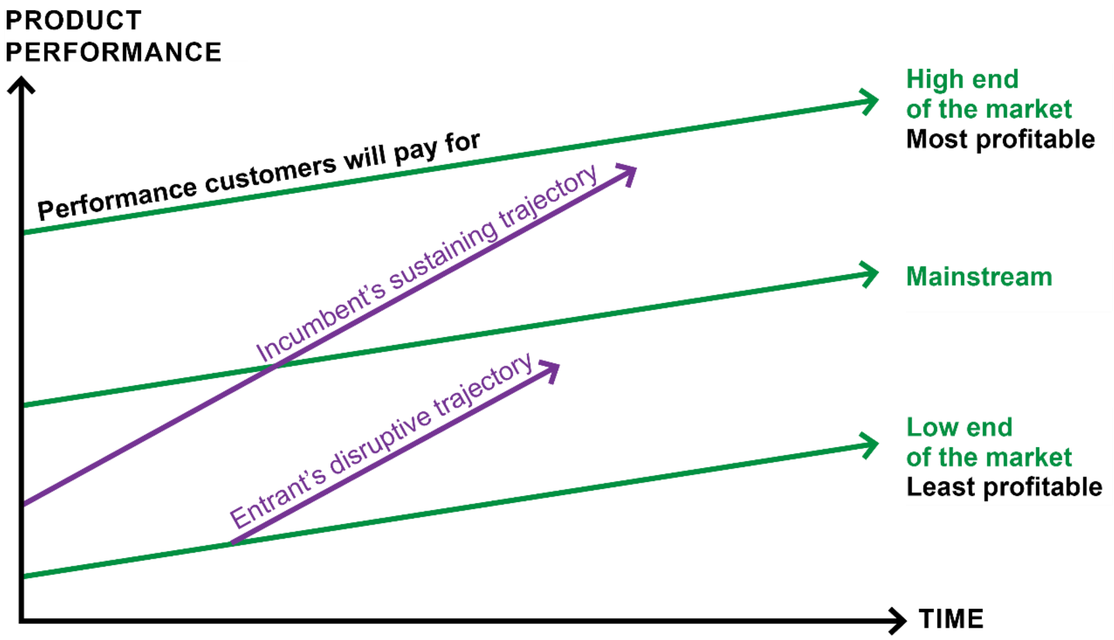

Figure 7: The trajectory of disruptive innovations, adapted from Christensen et al. (2015)

In this thesis, I refer to the classic view of disruptive technologies and disruptive innovations as the Christensen perspective. The Christensen perspective provides a good explanatory frame for stories such as that of Honda disrupting Harley Davidson, Netflix disrupting Blockbuster, and AirBnB disrupting the hospitality sector. In all of these cases, the disruptor entered the market from the fringe (the low-end or a new market) and offered a product that was significantly worse than the mainstream alternatives: A small motorbike, a DVD-by-mail service and a couch rental service (Christensen 1997; Christensen et al. 2015; Guttentag 2015).

However, the Christensen perspective has some shortcomings. While both Apple's iPhone and Tesla's electric cars have had a significant and game-changing impact on the markets for mobile phones and electric cars, respectively, none of these examples can be explained by classic disruption theory. Both innovations entered the market from the high-end by offering a premium product to the most demanding customers. Nevertheless, both cases resembles stories of disruptive innovation, and motivate the search for a different view on disruption.

3.1.3 A new view on disruption

This sub-section introduces the Gans (2016a) perspective on disruption, which combines the Christensen perspective on disruption with Henderson and Clark's (1990) notion of architectural innovation. In the following sub-section, I explain why the Gans perspective on disruption is well-suited for studying disruption in a complex systems sector such as construction.

Disruption as a phenomenon

In 2016, Gans reviewed disruption literature and proposed a redefinition of disruption theory. Rather than focusing on technological characteristics or market entrance strategies, he focuses on the impact of disruption on established companies. He defines a *disruptive event* to occur "when a product or technology enters the market causing successful firms to struggle" and defines disruption as a phenomenon:

> *"The phenomenon of disruption occurs when successful firms fail because they continue to make the choices that drove their success."*
> (Gans 2016a p. 9)

In his book "The disruption dilemma", Gans (2016a) outlines the theoretical foundation for disruption theory and situates disruption within the broader field of innovation management literature. Specifically, he draws on Henderson and Clark's (1990) notion of architectural innovation, and argues that this term is actually descriptive of a certain type of disruption.

Architectural innovation as a form of disruption

Henderson and Clark's (1990) seminal work distinguishes between four types of innovation: incremental, modular, architectural and radical innovation (see Figure 8). This classification is based on the observation that established companies tend to create organisational structures that mirror the primary components of their product (Colfer and Baldwin 2016). For example, in a company that produces room fans, one department could be concerned with the blades, another with the motor, and a third with the mechanical housing. Each department holds specialised component knowledge, whereas the communication channels between departments holds the necessary architectural knowledge. This organisational structure makes established companies efficient in implementing innovation on the component level (i.e. incremental and modular innovations), because this often can be executed within the organisational units. At the same time, however, the organisational structure also makes the companies vulnerable to innovations that change the ways in which components are linked (i.e. architectural and radical innovations). Henderson and Clark (1990) notably argue that architectural innovations are more challenging than radical innovations, because architectural innovations are harder to identify and implement. While a radical innovation might be implemented by creating new organisational units, an architectural innovation creates a need for restructuring the interfaces between the organisational units, while letting the core of organisational units remain unchanged. And that is a difficult change process to established companies.

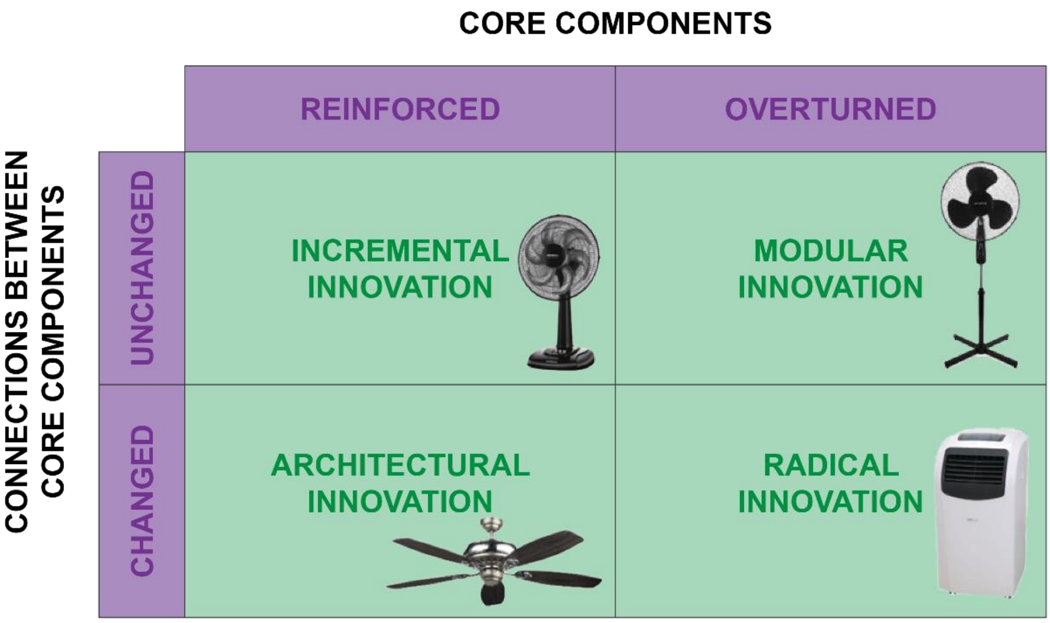

Figure 8: Four types of innovation, adapted from Henderson and Clark (1990)

Demand-side and supply-side disruption

Gans (2016a) juxtaposes the notion of architectural innovation and Christensen's theory of disruptive innovation, arguing that both terms describe why established companies fail as they face new technologies. Furthermore, he introduces the terms *demand-side disruption* and *supply-side disruption*: Christensen (1997; 2003) focuses on the *demand side* by arguing that disruption occurs as a result of established companies staying too close to their mainstream customers. In contrast, Henderson and Clark (1990) focus on the *supply side* by arguing that established companies fail when they focus too much on component innovation and not enough on innovating the architecture. Figure 9 illustrates the connections between the theoretical concepts of disruption, and how this theory has evolved over time.

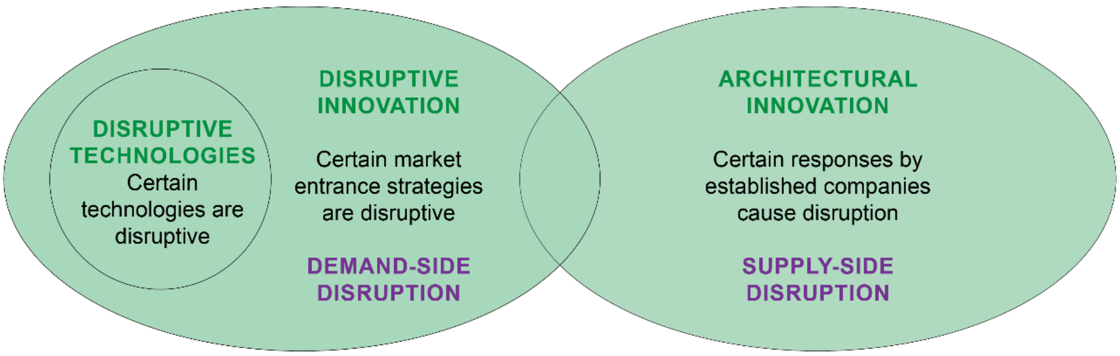

Figure 9: A conceptual illustration of the three perspectives on disruption and how they connect.

By combining the notions of disruptive innovation and architectural innovation, Gans' definition of disruption is able to explain stories of failure and success, such as those of Tesla and Apple. After the introduction of the iPhone, market leading companies such as Blackberry and Nokia struggled to maintain their market leading position (Gans 2016b). And, after the launch of

Tesla's Model S, every leading company in the automotive industry has begun investing heavily in battery-driven electric vehicles (Lezama 2016). Nonetheless, in both markets, incumbents such as Blackberry and Ferrari has struggled to maintain their market leading position (Gans 2016b; Lambert 2020).

While the Christensen perspective explains why incumbents *choose to ignore* disruptive innovations, the Henderson-Clark perspective explains why incumbents can be *unable to react* to disruptive innovations. The launch of the Apple iPhone and the Tesla Model S were not ignored by the competitors. But, these innovations fundamentally changed the product architecture of mobile phones and electric vehicles, respectively, making incumbents almost unable to react. In other words, these are stories of supply-side disruption.

3.1.4 Disruption in the context of this thesis

On an overall level, this thesis draws on Gans' (2016a) definition of disruption, which focuses on the effect of disruption to incumbents. This focus aligns well with the overall aim of this thesis, which is to study disruption from the viewpoint of established companies in the construction. This being said, my view of disruption has evolved during the course of the PhD and the thesis reflects this development. The first study commits to the Christensen perspective, as it investigates the applicability of classic disruption theory to a construction sector context. The second study commits to the Christensen's traditional notion of disruptive technologies, as it develops a list of 133 technologies that are potentially disruptive to construction. The third study intentionally avoids committing to disruption terminology, as it explores how innovation champions of the construction sector envisions the future – disruption or not. The fourth study draws on both the Christensen and the Henderson-Clark perspective, hereby committing indirectly to Gans' view of disruption, as it reports on the selection for 22 technologies with a game-changing potential to the construction sector.

3.2 Construction innovation

The construction sector is the main reference frame and application domain for this thesis. Linking the notion of disruptive innovation to construction innovation, I begin with a brief historic overview. The notion of disruptive innovation can be traced back to the economics Joseph Schumpeter, who in the beginning of the 20th century studied the effects of innovation on the economy. He characterised innovation as a critical dimension of economic change and explained how the introduction of a new product could incur "creative destruction", i.e. the destruction and reconfiguration of economic structures. The notion of creative destruction is often seen as a precursor of the notion of disruption (Woodhead et al. 2018).

With regards to the construction sector, the earliest notion of creative destruction is almost 100 years old. In the late 1930'ies, Schumpeter predicted that fabricated housing would bring a gale of creative destruction to the construction sector in the same way as mass production was revolutionising other industries (Winch 1998). More than half a century later, Winch (1998) found construction had not experienced the predicted revolutionary change due to mass production methods. Winch suggested that innovation dynamics of construction is significantly different from that of other industries, and called for more research on what characterises innovation in construction.

In the following, I will outline how the construction sector context (which was described in chapter 2.1) affects innovation in the sector. Drawing on literature, I define construction innovation, describe how it differs from innovation in other sectors and present ‘innovation champions’ as important drivers of innovation in the construction sector. Next, I describe different types of construction innovation and position disruptive innovation research within construction innovation literature. I find that digital technologies drive research on disruptive innovations in construction, and discover a need for more foresight-enabled research that highlights the transformative power of digitalisation to construction.

3.2.1 Characterising construction innovation

Defining construction innovation

Within the field of construction, Slaughter’s definition of innovation is broadly recognised by researchers and practitioners (Blayse and Manley 2004):

> *“An innovation … is defined as a non-trivial improvement in a product, process, or system that is actually used and which is novel to the company developing or using it”* (Slaughter 2000 p. 1466).

This definition emphasises that an innovation is more than a (technological) invention. Moreover, it emphasises that an innovation, unlike an invention, is not necessarily novel to the world, but it is novel to the organisation creating or adopting it. In other words, when speaking about innovation, context matters.

Distinguishing construction innovation from innovation in other sectors

Slaughter (1998) proposes five ways in which the construction context affects the innovation dynamics in the sector:

- The construction sector create *large-scale* facilities, which are assembled on site. This limits the applicability of innovations that require controlled testing environments, and make full-scale testing expensive and time-consuming.
- Construction facilities are *complex* and consist of many interdependent systems, which are not comprehensively characterised. This makes it difficult to trace the far-ranging effects of implementing an innovation.
- The *long expected lifetime* of build structures makes it necessary to test innovations over a very long time and include strategies for repairing and modifying the innovation through several decades.
- Constructing a built structure involves a number of diverse stakeholder groups, who work together on a project. Correspondingly, innovation is typically carried out in projects and require *interorganisational negotiation.*
- To ensure the safety, health and well-being of people, *a large number of codes and guidelines* regulate the design, construction and operation of construction facilities. These regulations also affect innovation.

In other words, the form, size, complexity and societal importance of construction products affect how innovation is carried out in the sector. Considering the rather unique characteristics of the construction sector, one should be careful in comparing the sectoral rate of innovation to that of other sectors (Winch 2003b). That said, much research aligns in describing the construction sector as conservative and lagging behind other sectors when it comes to implementing innovation (Bygballe and Ingemansson 2014; Winch 1998; Xue et al. 2014). Several industry analysis reports concur with this view, and highlight a great potential for improving productivity of the sector by means of technological innovation (Barbosa et al. 2017; World Economic Forum 2016).

Driving construction innovation by means of champions

When innovation does happen in construction, it is often driven by key individuals, known as innovation champions (Winch 1998). Innovation champion is not a job title, rather it is a descriptor of certain inspirational individuals, who persistently promote innovation despite opposition (Leiringer and Cardellino 2008). Innovation champions act as change agents as they gain commitment to their ideas by telling convincing narratives of the future (Sergeeva 2016). Furthermore, Nam and Tatum (1997) emphasise that innovation champions need to be technically competent to overcome the uncertainty and resistance towards innovation. Multiple studies confirm the importance of innovation champions to the diffusion of innovation. Correspondingly, much research considers these individuals to be key informants in understanding the innovation dynamics of construction (Leiringer and Cardellino 2008).

Research shows that certain innovations are more easily implemented in construction than others (Taylor and Levitt 2004). In the next sub-section, I describe different types of innovation and their characteristics.

3.2.2 Categorising construction innovation

Much research have investigated how to differentiate between different types of construction innovation. Slaughter (1998) proposed that innovation is classified on a 5-point scale from incremental to radical based on the degree of required change. Harty (2008) criticised this single-dimensional classification of innovation, as it does not pay attention to the context of implementation. He describes construction innovation as relatively unbounded, because the implications of an innovation typically cannot be contained within the control of one organisation.

Henderson and Clark (1990) observed that certain innovations can create relatively modest changes to existing technologies and still induce rather dramatic changes to the competitive position of an organisation. As described in chapter 3.1.3, Henderson and Clark (1990) proposed four types of innovation: incremental, modular, architectural and radical innovation. Transferring Henderson and Clark’s framework to the construction sector context, Taylor and Levitt (2004) propose extending its intra-organisational focus to include innovation dynamics between organisations. Furthermore, Taylor and Levitt replace the notion of architectural innovation with that of *systemic innovation* to describe innovations that cross organisational boundaries.

According to Hall and Lehtinen (2015), Sheffer and Levitt (2012) found that systemic and systemic innovations diffuse up to three times slower incremental and modular innovations (Hall and Lehtinen 2015). Because systemic and radical innovations require changes to the way in which work is organised within the sector, these innovations are actively resisted by the current industrial structure. Nevertheless, construction researchers emphasise the importance of implementing systemic innovations to leverage much needed disruptive changes in the sector:

> *"The prevailing product architecture and paradigm can only change through disruptive "systemic" innovations that overturn the current product architecture paradigm! What will be the disruptive paradigm for construction? … More work is needed in this area to understand the dynamics of learning in firm networks in our mature, project-based industry"*
> (Levitt 2007 p. 625)

In this thesis, I frame systemic innovation as a specific kind of disruption. Drawing on Gans (2016a), I propose that the notion of systemic innovation can be used to describe supply-side aspects of disruption, whereas the notion of disruptive innovation can be used to describe both supply-side and demand-side aspects of disruption (see chapter 3.1.3). Systemic innovation literature focus on the inter-organisational barriers to implementing change in the construction sector. As a complementary stream of literature, demand-side disruptive innovation literature focus on how technologies affect the competitive position of established companies. By drawing on both streams of literature, I combine a sector-wide perspective with a company-level perspective to investigate the implications of digital technologies on construction.

3.2.3 Digitalisation as a driver for research on disruptive innovation in construction

Much research on disruptive innovation in construction is driven by the rise of digital technologies. As described in chapter 2.2, digital technologies possess the ability to break sectorial boundaries and reorganise the way in which information is stored, transmitted and processed. Correspondingly, the implementation of digital technologies affect the relationships within and between construction companies (Erdogan et al. 2010; Hall 2018). Systemic innovation literature describes how companies need to facilitate innovation that changes business organisation and processes to achieve the full benefits of digitalisation (Hall 2018). Other researchers use the notion of disruptive innovation to describe the game-changing potential of digital technology and to highlight the threat of digital platform giants such as Google and Facebook entering the construction sector (Lavikka et al. 2018; Singh 2019). In the following, I will provide a brief overview of how digital technologies are portrayed in academic literature on disruptive innovation in construction.

Recently, the concept of disruption has become popular among construction researchers. Reviewing literature, I find that much of this research use the theoretical notion of disruption to study the implementation of a specific digital technology. This may be additive manufacturing (Ghaffar et al. 2018; Kothman and Faber 2016; Salet et al. 2018), blockchain (Li et al. 2019; Perera et al. 2020; Veuger 2018), construction automation (Bock 2015), or Building Information Modelling (BIM) (Morgan 2017; Poirier et al. 2015). However, despite the widespread use of the notion of disruptive technology, only few researchers (e.g., Kothman and Faber 2016) define what they mean by the term.

Compared to the vast body of research on particular disruptive technologies, only a few construction researchers highlight the importance of looking at multiple digital technologies in combination (Singh 2019; Woodhead et al. 2018). Within this sub-group of research, the notion of disruption is used to emphasise the transformative power of digitalisation to the sector (Lavikka et al. 2018; Singh 2019; Woodhead et al. 2018). To anticipate the expected impact of digitalisation, Lavikka et al. (2018) and Singh (2019) highlight the benefits of using foresight methods. This thesis complements such research by using foresight methods to explore the disruptive effects of multiple, digital technologies on the construction sector. The next section will therefore provide an introduction to futures studies in general, and construction futures studies in particular.

3.3 Construction futures

As reflected in the research questions (presented in chapter 1.3), this thesis studies the future of the construction sector. To provide a theoretical framing of the thesis, this section introduces current research on futures studies in construction.

3.3.1 Defining futures studies

Multiple definitions of futures studies exist, as this field is interdisciplinary and evolving (Dannemand and Rasmussen 2012). In this thesis, I use the term futures studies to refer to a field of research, and the term foresight to refer to certain methods and processes within this field. To characterise the evolving field of futures studies, I draw on a definition by Kreibich et al. (2011):

> *"Futures studies are the scientific study of possible, desirable, and probable future developments and scope for design, as well as the conditions for these in the past and in the present."* (Kreibich et al. 2011 p. 9)

Futures studies typically take the point of departure in complex dynamic systems, as they study the medium- to long-term implications of current decisions and actions to the system (Kreibich et al. 2011). Modern-day futures studies commit to the belief that the future cannot be predicted or determined (Dannemand and Rasmussen 2012). Rather, multiple possible futures exist, and these are not arbitrary (Kreibich et al. 2011). Citing Steinmüller (1997), Kreibich et al. (2011) propose three special features of futures studies research:

- *Verification:* When studying the future, the findings cannot be verified at the time they are stated. Steadfast foresight processes enhance the reliability of results.
- *Participation*: When studying the future, research objects cannot be studied in isolation from their environment. Participatory processes enhance the quality of results.
- *Long-term orientation:* When studying the future, a time horizon of 5-50 years is suitable. This means that futures studies start at the point in time where traditional planning tools ends.

Collectively, these special features entails that much futures studies research is descriptive and exploratory (Dannemand and Rasmussen 2012). Futures studies apply a broad range of exploratory, analytical, or anticipative foresight methods; some of which are also known from other fields of research. The most widely used foresight methods include literature review, expert panels, scenarios, trend extrapolation, futures workshops and brainstorming (Popper 2008). This thesis uses foresight methods such as horizon scanning, interviews, visioning, and workshops to explore the implications of digital technologies on the future of construction.

3.3.2 Futures studies in construction

Within the domain of construction, futures studies are often used to explore how the sector can improve its overall performance (Chan and Cooper 2011). Construction researchers highlight that one of the main benefits of futures studies is that these studies prompt construction stakeholders to think about how they will respond to possible future changes (Dixon et al. 2018;

Harty et al. 2007). However, even though futures studies can help improve decision making in construction companies, Soetanto et al. (2007) find that there is little capacity for long-term planning in construction companies. Moreover, Dixon et al. (2018) finds that most construction futures studies are rather short-term oriented, and recommend that the construction sector expands its planning horizons beyond a few years to prepare for future change.

Construction researchers acknowledge that one of the most important outcomes of futures studies comes from participating in the process, rather than by reading the end result (Harty et al. 2007; Soetanto et al. 2007). Correspondingly, construction futures researchers emphasise the importance of involving a broad range of stakeholders in foresight processes, rather than selecting a few experts to envision the future (Chan and Cooper 2011; Harty et al. 2007; Soetanto et al. 2007). Moreover several researchers have identified a need for making the abstract future more tangible to stakeholders (Chan et al. 2005; Lavikka et al. 2018). Correspondingly, the research presented in this thesis engages multiple stakeholders in envisioning the future of construction and aims to make the implications of digitalisation as tangible to practitioners.

Reviewing current futures studies of construction, Harty et al. (2007) found that most studies fail to imagine radically transformed futures of construction. Instead, construction futures studies tend to merely extrapolate current trends and envision a future that is incrementally different from the present (Chan and Cooper 2011; Dixon et al. 2018; Harty et al. 2007). This is unfortunate, considering that digital technologies may result in disruptive changes that can make it difficult for established companies to remain competitive. Correspondingly, this thesis applies long-term oriented foresight methods to study potential disruption of the sector.

All in all, this brief review of construction futures literature emphasises that futures studies in construction should be long-term oriented, engage multiple stakeholders, make the future tangible for practitioners and consider futures that are radically different from today.

3.4 Chapter summary

To introduce the theoretical framing of this thesis, this chapter:

- Presented three well-established perspectives on disruption:
    - disruptive technologies (Christensen 1997),
    - disruptive innovations (Christensen and Raynor 2003), and
    - disruption as a phenomenon (Gans 2016a).
- Described how this thesis uses all three perspectives to explore the applicability of disruption theory to a construction context.
- Scoped the thesis to focus on established companies and correspondingly argued for the relevance of committing primarily to the Gans perspective on disruption.
- Introduced the notion of architectural innovation, and its counterpart in construction: systemic innovation.
- Connected literature on systemic innovation to literature on disruption and argued that systemic innovation can trigger supply-side disruption of construction.
- Defined and characterised construction innovation, arguing that innovation in this sector is significantly different from that of other sectors.
- Introduced the notion of ‘innovation champions’ to describe individuals who drive innovation in the construction sector, despite opposition.

- Reviewed literature on disruptive innovation in construction and presented digitalisation as an important driver of such research .
- Discovered a need for research that considers the potentially disruptive implications of multiple technologies in combination, and argued for the relevance of using foresight methods to conduct such research.
- Defined and introduced futures studies as an interdisciplinary, participatory and long-term oriented research area.
- Elicited a need for long-term oriented construction futures studies that involves multiple stakeholders and make the implications of digitalisation tangible to stakeholders.
- Elicited a need for exploring futures of construction that are radically different from today.

4. Methodology

In the previous chapters, I have described the problem domain (digital technologies creating large-scale changes in the construction sector) and theoretical framing (disruption literature complementing future-oriented construction innovation). Moreover, I have outlined the shortcomings of existing literature in describing how multiple digital technologies affect established construction companies, and presented the overall aim of this research: To aid established construction companies in navigating in digital futures. Consistent with this highly practice-centred aim, I take a pragmatic approach to research. A pragmatic research approach is suitable, when research is driven by a problem and aims at developing practical solutions (Robson and McCartan 2016; Saunders et al. 2019).

This thesis applies a future-oriented design approach to research. This research approach developed organically as described in the following. First, I describe my designerly approach to the research, which included using design abduction and frame-creation. Next, I use the Design Research Methodology (DRM) framework to present the four main studies of the thesis. Then, I describe the selection and combination of research methods from the fields of design and futures studies. Finally, I present and connect the four papers that form the main body of this thesis.

4.1 Research approach: Design research

The previous chapters outlined how companies in the construction sector are embedded in a complex stakeholder network, and how digital technologies add uncertainty to the already dynamic market landscape. In other words, the problem at the centre of this research project is both complex, dynamic and networked (Dorst 2015). To appreciate the complexity of the problem, I take a designerly approach to research (Cross 1982). A designerly approach is well-suited for addressing truly complex problems, which require an entire system to be brought forward into a more desired state (Dorst 2018). In this case, the ‘system’ is the construction sector and the ‘desired state’ involves realising the potential benefits of digitalisation.

In these years, the field of design and the notion of design thinking receive increasing attention (Dorst 2011). Researchers and practitioners have discovered the benefits of a design thinking approach to problem solving in situations of uncertainty and ambiguity (Dym et al. 2006). Considering the ubiquitous nature of digitalisation and its far-ranging consequences, it is perhaps not surprising that design thinking is now considered the new paradigm for problem solving within information technology and business (Dorst 2011; Fraser 2009; Stevens and Moultrie 2011). Design thinking differs from traditional business thinking as it emphasises the qualities of being exploratory and imagining what could be, opposed to a more analytical focus on efficiency (Clatworthy 2011).

While many definitions of design and designing exist, design researchers tend to agree that design research has two general dimensions: one concerned with understanding the complexity of a problem situation, and one concerned with improving the situation (Blessing and Charkrabarti 2009; Frankel and Racine 2010).

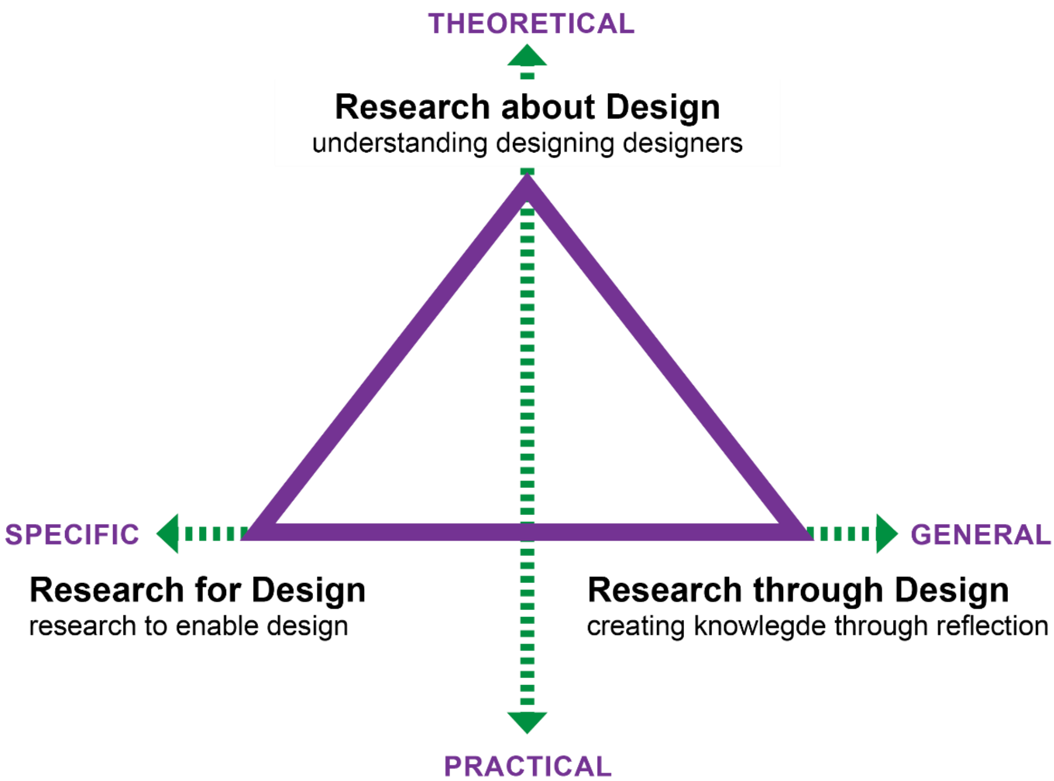

Figure 10: Conceptualising design research, adapted from Tieben (2015). Original source: Frankel and Racine (2010).

Design research is multifaceted, encompassing research about design, research for design and research through design (see Figure 10). This thesis focuses on the practical aspects of design research, i.e. the bottom part of Figure 10. The thesis starts by conducting research to enable design (in the bottom left) and gradually moves to the right to conduct research through design to improve the current situation.

4.2 Research strategy

A designerly approach to research acknowledges that in a complex system, "*change is achieved through influencing the system (rather than through implementing a plan to "solve the problem")*" (Dorst 2018). Correspondingly, I will not suggest that one particular solution can solve the issues of digital technologies entering construction. Instead, I develop a research strategy that explores multiple possible ways in which the construction sector can deal with digital technologies. As is typical for design research, I apply an open form of reasoning, called design abduction.

4.2.1 Reasoning by means of design abduction

Typically, research differentiates between three kinds of reasoning: Deduction, induction and abduction (Saunders et al. 2019). Dorst (2015) explains these three kinds of reasoning by means the formula depicted in Figure 11.

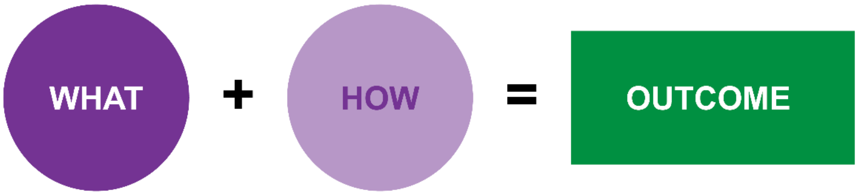

Figure 11: Design abduction as a form of reasoning, adapted from Dorst (2015).

Deduction involves predicting an OUTCOME based on knowledge of WHAT a thing (an object/service/system) is and HOW it works. This could e.g. involve predicting the location of a star at a specific point in time based on knowledge of how stars move in the sky. In contrast, induction involves proposing HOW a thing works based on knowledge of WHAT it is and knowledge of what OUTCOME it generates. This could e.g. mean using observations of stars to propose a new law for how they move in the sky. Both deduction and induction are analytical ways of reasoning that can help us *understand* various phenomena.

Abduction, in contrast, is a form of reasoning that aspires to *create* a certain outcome. Conventional abduction (abduction-1) involves producing a thing (the WHAT) based on knowledge of the desired OUTCOME and HOW things work. Dorst (2011) proposes a fourth type of reasoning which he calls abduction-2. This designerly type of reasoning involves producing a desired OUTCOME without knowing neither WHAT or HOW this outcome is to be obtained. Abduction-2 is relevant for open, complex problems, such as the one presented in this thesis. Designers, who use abduction-2 reasoning, typically strive to develop or adopt a frame, which suggests that a certain HOW can lead to the desired OUTCOME.

4.2.2 Framing and reframing the project

The frame-creation process is central to the field of design (Dorst 2011). This process helps designers understand the complexity of a problem, and bypass the assumptions that is inherently present in the original formulation of the problem. To create alternative frames, designers typically draw on the experiences from other disciplines, arguing that the type of logic, which was used to create the problem, is not the kind of logic that should be used to solve it (Dorst 2018).

When I initiated this PhD, the desired outcome of the project might be defined as “a construction sector that avoids being disrupted”. This framing was built upon the basic assumption that a construction company could avoid being disrupted if it implemented one or more critical technologies. If I had maintained this framing of the PhD, I would presumably have assessed the disruptive potential of different technologies, selected a 1-3 technologies as the most important ones and initiated an implementation.

However, approaching the problem as a design researcher, I did not commit to the initial framing of the project. Instead, I analysed the problem situation from various points of views. To understand the multifaceted concepts of disruption, technology and futures, I drew on knowledge from multiple research fields: innovation management, technology management, futures studies and design and applied it to construction. In this process, I gained multiple insights. Two important insights guided the development of a research strategy:

1. Technologies overlap, evolve and connect. Anticipating the effect a single technology is therefore somewhat artificial. A combinatorial view of multiple technologies may be a beneficial approach.
2. Construction sector stakeholders are focused on short-term profits and low-risk innovation. To grasp the implications of disruptive innovations, it may be beneficial to create long-term visions.

Based on these insights, I reformulated the desired outcome to be “a construction sector that exploits the benefits of digital technologies”. Moreover, I experimented with several ways of framing HOW this outcome was to be obtained. The final framing of the project could be formulated as follows: “A long-term-oriented perspective can help construction stakeholders remove focus from the current barriers to change, and facilitate constructive dialogue on the potential of digital technologies.” In other words, I reframed the thesis from focusing on the potential of one or more specific technologies to focus on the potential futures enabled by multiple, digital technologies. This led me to formulate the research questions presented in chapter 1.3.

By specifying the desired outcome, reframing the research project and formulating research questions, I have now described my approach to research. The following sections will build on this foundation by describing how I designed and structured the actual research.

4.3 Research structure

Design research can be structured in many ways. This thesis commits to the Design Research Methodology (DRM) as this is a multidisciplinary and versatile framework for structuring design research (Blessing and Charkrabarti 2009). The DRM emphasises how design research typically combines studies that strive to *understand a situation* with studies that strive to *improve the situation*. In this case, I aim to *understand* if and how digital technologies may affect construction, and develop support to *improve* the situation for established companies.

The DRM structures design research into four phases: research clarification, descriptive study I, prescriptive study and descriptive study II (Blessing and Charkrabarti 2009). In the first phase, research clarification, the research goals and success criteria are clarified. In the next phase, descriptive study I, the current situation is illuminated by collecting empirical data, studying literature and analysing the findings. In the third phase, the prescriptive study, an increased understanding of the current situation is used to develop some kind of support to improve the situation. In the fourth phase, descriptive study II, the applicability of the support is evaluated and further action devised. The DRM framework is adaptable as the phases may be completed iteratively and/or in parallel. Some research projects may go through only some of the phases, and other research projects may go through all the phases several times.

The research presented in this thesis is structured according to the DRM framework as seen in Figure 12. The thesis builds on four separate, yet interconnected, studies. To obtain a comprehensive understanding of the problem domain, three studies form descriptive study I. These three studies investigate the terms disruption, technology and futures, respectively. The fourth study constitutes the prescriptive study, as it develops support for construction companies to improve the current situation. Although the fourth study includes an initial evaluation of this support, the thesis does not engage in a comprehensive descriptive study II.

Figure 12 shows how each study contributes to answering the research questions. The overall research question, RQ1, is answered by synthesising the results from all four studies.

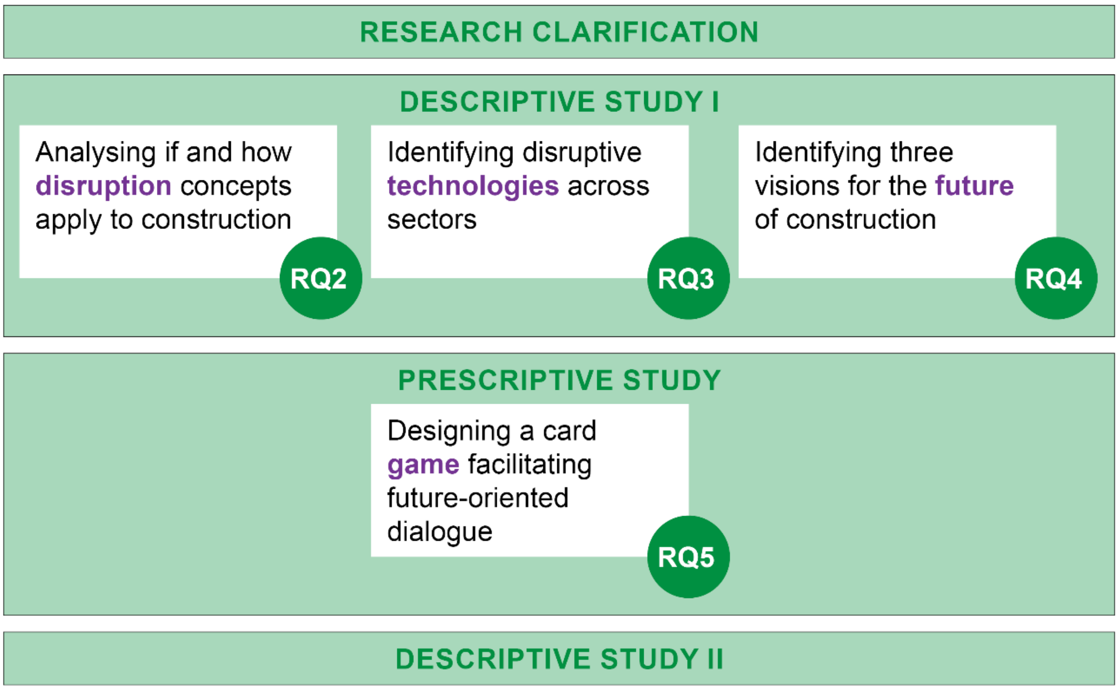

Figure 12: The Design Research Methodology framework visualising the research structure, adapted from Blessing and Charkrabarti (2009).

4.4 Research methods

As is common for design research, the selection of relevant research methods was carried out in a goal-directed and flexible manner (Blessing and Charkrabarti 2009). In this thesis, I primarily draw on qualitative research methods as these are well-suited for studying a phenomenon (i.e. disruption) within its empirical context (i.e. construction) (Robson and McCartan 2016). The research questions centre around anticipating the future, and correspondingly, I find it relevant to draw on the field of futures studies. As described in chapter 3.3, futures studies are concerned with anticipating how complex dynamic systems will be affected by decisions and actions on the medium- and long-term (Kreibich et al. 2011).

This thesis combines research methods from the fields of design and futures studies. These two fields share many similar characteristics. Whereas design aims at designing a product, process or system, futures studies aim at anticipating possible, probable and desired futures. A typical futurist approach may involve framing the current conditions, identifying signals of change, generating several alternative futures, committing to one preferable future and developing strategies to obtain this future. This process is similar to a typical design process, and correspondingly, some methods are applied by both fields, e.g. interviews, surveys, and brainstorming. The pragmatic research approach encourages the selection and combination of multiple methods to fit a given context. The following sub-sections describes my selection of methods.

4.4.1 Question-driven, comparative literature analysis

The first study provides an enhanced understanding of the disruption phenomena. Here, I let my choice of research method be guided by the overall question “Is the construction industry really ripe for disruption?”. Studying both academic and grey literature, I discovered that the healthcare sector, similarly to construction, is claimed to be ripe for disruption. I was driven by curiosity, as to understand what made both these large and societally important sectors ripe for disruption and I therefore decided to do a comparative literature analysis. The Disruption Paper (Ernstsen et al. 2018a) describes this analysis, which was driven by three questions, concerned with why, when and how disruption is expected. In the paper, we identify a number of common characteristic of the two sectors and apply the theoretical principles of disruption literature to a construction context to explore when and how disruption may manifest. In this way, the methods applied in the first study are highly goal-directed. Although there is considerable uncertainty connected to anticipating aspects of the future, I find that the study is useful for exploring the practical applicability of disruption theory.

4.4.2 Horizon scanning and interviews

The second study provides an enhanced understanding of which specific technologies that may be disruptive to construction. In line with the initial framing of the PhD project, the focus of this study is to create a long list of potentially disruptive technologies. To find an appropriate technology identification method, I reviewed literature on futures studies and technology management. In futures studies literature, I found that many traditional foresight methods anticipate the future by extrapolating trends and technological trajectories. Correspondingly, traditional forecasting and foresight methods struggle to foresee disruptive changes (Cheng et al. 2017; Dixon et al. 2018; Georghiou and Harper 2013). In technology management literature, I found that companies can apply one of four technology intelligence modes to gain knowledge about technology: mining, trawling, targeting and scanning (Kerr et al. 2006) (see Figure 13).

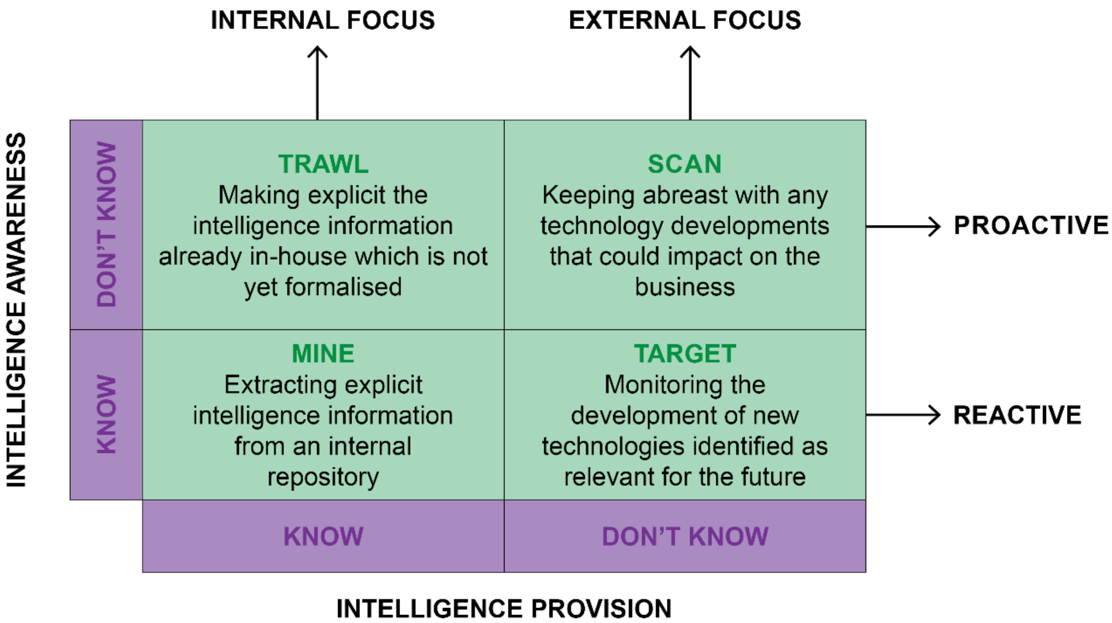

Figure 13: Four modes for obtaining technology intelligence, adapted from Kerr et al. (2006).

The mining and trawling modes are useful for extracting knowledge from within the company, whereas the targeting and scanning modes are useful for obtaining information from the external environment. In situations with great uncertainty or risk of disruption, companies can benefit from employing the scanning mode, as this mode is appropriate when a company does not know what it does not know (Kerr et al. 2006).

Committing to the scanning mode, I decided to conduct an exploratory horizon scanning (Amanatidou et al. 2012). This foresight method is suitable for identifying incipient trends and emerging technologies across multiple domains (Sutherland et al. 2011). The Horizon Scan paper (Ernstsen et al. 2018b) describes how we reviewed 11 reports and 9 practitioner-oriented conferences, resulting in a list of 133 potentially disruptive technologies. The paper also describes the challenges connected to validating such a list of technologies, as only the future can tell, which technologies the future holds. We therefore approached the validation process through triangulation, and compared the results of the horizon scanning with the results of 25 short interviews with industry practitioners. The comparison shows that the horizon scanning successfully identified all the technologies, that the interviewees found important. Although this does not validate the list, it does indicate that the horizon scanning method is suitable for identifying a comprehensive list of relevant technologies.

4.4.3 Semi-structured interviews and qualitative coding of transcriptions

The third study provides an enhanced understanding of digital futures. Whereas the first two studies look at the construction sector development from the outside-in, this study acknowledges the role of the stakeholders within the construction sector in affecting the sector from the inside-out. To explore what construction practitioners expect with regards to digitalisation of construction, we decided to conduct qualitative, semi-structured interviews with construction practitioners. The Vision paper (Ernstsen et al. 2021) describes how we sampled interviewees that we considered innovation champions, and how we conducted the interviews in an open-ended, exploratory fashion. Furthermore, the paper describes the iterative and qualitative coding of the interview transcriptions, which results in the identification of 27 future aspects. As is common for qualitative research, the study provides in-depth insights into a phenomenon in its empirical context. These in-depths insights are created on the expense of generalisability, and correspondingly, the findings cannot necessary be replicated or transferred to another context. However, the qualitative coding of interview transcription did result in an important contextual insight: We observed, that when the interviewees described the future of construction, certain interviewees would mention particular technologies and trends, and other interviewees would mention a different set of technologies and trends. To us, this indicated the existence of different narratives about the future. To confirm or disprove the existence of different future narratives, we decided to apply network analysis.

4.4.4 Network analysis and visioning

Network analysis is a quantitative research method for studying the relationships between different elements in a complex system (Piccolo 2019). Network analysis is situated within the field of network science, and is well known for its ability to illustrate the relationships between people in a social media network. The Vision Paper describes how we used network analysis to visualise connections between technologies and trends, and how we subsequently used an algorithm to identify three clusters in the network. Using our qualitative insights from the interviews to interpret the results, we find that the clusters represent three narrative visions for the future. To contextualise the findings, we also compare the three visions to current discourses in the sector. In this way, the Vision paper reports on a mixed method approach that combines both qualitative and quantitative methods to obtain a conclusion. Although multiple other interpretations of the same data are possible, the triangulation of data contribute to consolidating the results.

4.4.5 Design games and workshops

The fourth study is a prescriptive study that aims at helping established construction companies to navigate among digital technologies. As one of the main activities in design involves developing solutions to improve the current situation, we consulted design literature to select an appropriate method for this study. We found that design games are good at making abstract concepts, such as digitalisation, tangible. Correspondingly, the Technology Card Paper (Ernstsen et al. n.d. under review) describes the iterative development and testing of a design game, which presents 22 digital technologies relevant to construction. By testing the game in 17 workshops (called *Tech Sessions*), we find qualitative evidence for the applicability of the cards to facilitate future-oriented dialogues on digital technologies. The paper does not engage in measuring the concrete effect of the cards. As described by Peters et al. (2020), it can be difficult to measure the effects of a design game without a controlled testing environment, which is often impractical in real world settings. As the *Technology Cards* are designed to facilitate a context-dependent dialogue on the potential of technologies, I argue that it is contra-productive to create a standardised way of using the cards to obtain reproducibility of the results. Instead, the paper provides concrete examples of how the cards and the workshop format were customised to the context to obtain results that were valuable to the context.

4.5 Introducing the four papers

Four papers form the main body of this thesis. Whereas the previous section described how we selected the methods applied in each paper, this section zooms out to describe how the papers connect and contribute to shaping the thesis. I visualise how the papers link different bodies of literature to study technologies in construction, and describe how the papers builds upon each other to form the thesis.

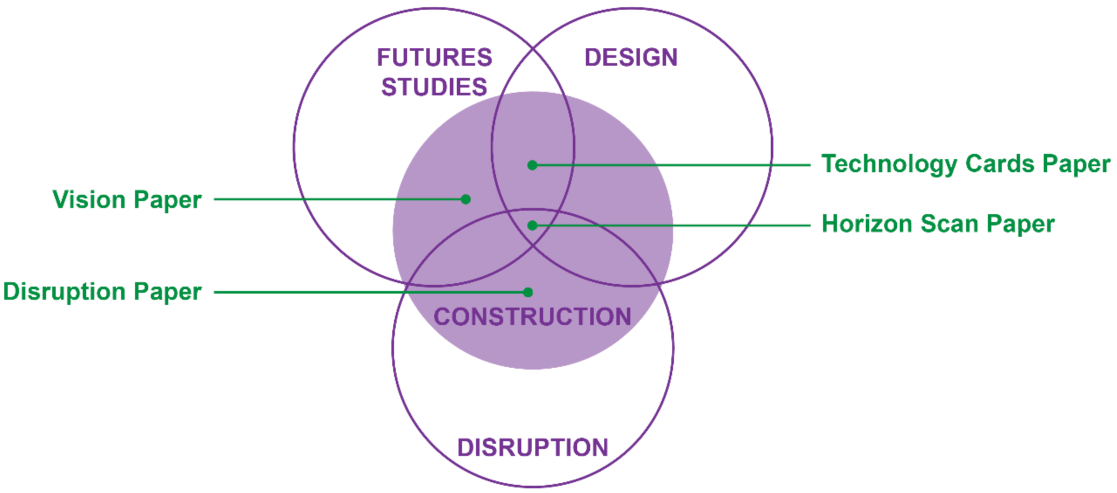

Figure 14: The four papers study the construction sector, drawing on insights from multiple fields

The research presented in this thesis may be visualised in many ways. Figure 14 visualises the research context for the four papers as three theoretical domains, which are applied to one empirical context. The Disruption Paper studies the application of disruption literature to the construction domain. The Horizon Scan Paper connects all three theoretical domains as it uses a foresight method in a design context to identify disruptive technologies. The Vision paper explores different futures of construction, and the Technology Cards Paper connects futures studies and design by developing a future-oriented design game. Collectively, the four papers demonstrate the benefits of drawing on fields of design, futures studies and disruption, when studying the implications of technology to the construction sector.

The four papers connect, as the findings from one paper contribute to motivating questions for the following paper (see Figure 15). By studying the applicability of disruption theory to a construction context, the Disruption Paper discovers how predicting the future is difficult, if not impossible. The paper also discovers that technology seems to play an important role in disruptive futures, and proposes that an anticipatory foresight approach may be suitable for investigating the implications of disruption to construction. The Horizon Scan Paper builds upon these insights, as it shows how a foresight method, namely horizon scanning, can be used to identify potentially disruptive technologies. By identifying 133 technologies across multiple sectors, this paper finds that the majority of emerging technologies are digital. To enhance the relevance of the findings to a construction context, the paper suggests complementing the cross-sectoral technology identification method with an issue-centred approach. Correspondingly, the following paper, the Vision Paper, concentrates on the construction sector, as it outlines three visions for digitalisation of construction. This paper finds that a multiplicity of visions can help frame future-oriented dialogues, as they emphasise the inherent uncertainty connected to planning for future. To facilitate these future-oriented dialogues in practice, the Technology Cards Paper presents the *Technology Cards* design game. This paper describes the selection of 22 high-impact technologies and demonstrates how a card-based design game can help construction stakeholders make digital technologies an integral part of strategies for the future.

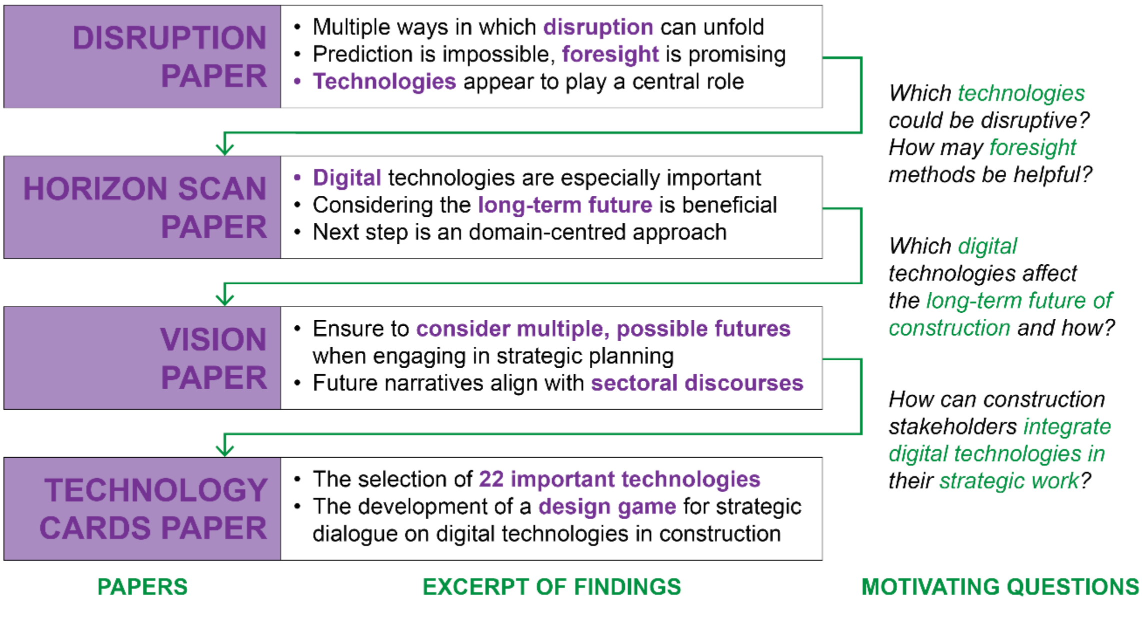

Figure 15: Visualisation of how the four papers build on top of each other to form the thesis.

4.6 Chapter summary

To account for the choice of research methodology, this chapter:

- Justified why this thesis applies a pragmatic, future-oriented design approach to research.
- Introduced the multifaceted field of design research.
- Described different kinds of reasoning, and argued for why this thesis primarily uses design abduction.
- Presented the frame-creation process as an important part of design and described how the research project was framed and later reframed.
- Outlined the research structure by means of the Design Research Methodology framework.
- Described and justified the selection of research methods for the four papers.
- Introduced the four papers that form the main body of the thesis, and described how the findings from one paper motivated the next paper.

5. Papers

This thesis builds on four papers. This chapter introduces the four papers by summarising the core insights from each paper. Please see the appendices for the full length papers.

5.1 The Disruption Paper: Exploring the theorical implications of disruption

This paper is found in Appendix A. The aim of the Disruption Paper is to investigate whether construction is indeed ripe for disruption. Through a comparison of two large sectors, construction and healthcare, the Disruption Paper identifies six characteristics of an industry ripe for disruption. These six characteristics are:

- Complex stakeholder networks
- Suboptimal incentive structures
- Fierce competition
- Low quality of offerings
- Skill-levels not aligned with tasks
- Lopsided innovation investments

These characteristics can indicate that construction is ripe for disruption – however, as discussed in the paper, the characteristics can also be used for arguing that construction (similar to healthcare) is impervious to disruption. Next, the paper discusses the inability of disruption theory to predict when disruption will occur, and proposes that construction stakeholders instead focus on exploring how disruption may unfold. To do this, the paper applies four recommendations from Christensen's disruption theory to construction practices. Table 2 summarises the applicability of each of these recommendations to construction practices.

All in all, the paper explores to which extent Christensen's theory of disruption can aid construction practitioners in anticipating changes. The paper proposes that to overcome the theory's inability to predict disruption, construction stakeholders can benefit from using foresight methods to envision possible disruptive futures of the sector.

Table 2: Transferring recommendations from disruption literature to a construction context

RECOMMENDATION FROM THEORY	RECOMMENDATION TRANSFERRED TO CONSTRUCTION PRACTICE	EXAMPLES OF HOW IT MAY UNFOLD IN CONSTRUCTION
Disruptive technologies: Be first movers	Being a first-mover is costly and risky. Stakeholders need to act simultaneously to create change.	The implementation of building information modelling (BIM) enable new digital value propositions. Automated construction technologies, e.g. robotics and 3D printing, may radically change production techniques.
Low-end disruption: Identify overserved customers	Most construction companies offer a wide range of services. A wide portfolio overshoots the needs of the least demanding customers.	Companies may package offerings to target specific jobs to be done, e.g., altan.dk. This also allows for automating simple tasks.
New-market disruption: Identify current non-consumers	A large number of stakeholders are involved in construction projects, however the users of a new built structure are difficult to involve.	Technologies may empower users to contribute to construction project, hereby creating new markets.
Focus on creating value for the customer	A need for rethinking contractual structures to align risk and reward. An increased focus on utilising data from the operation of built structures.	The value of a finished construction project could be measured in terms of e.g. quality of indoor climate or life-time environmental impact.

5.2 The Horizon Scan Paper: Searching for disruptive technologies

This paper is found in Appendix B. The Horizon Scan Paper is motivated by a desire to discover which technologies could disrupt construction. The paper reviews the notion of technology, and finds that the term ‘technology’ is wide-ranging, as it may refer to an artefact, process or human practice. Moreover, a technology can be an umbrella term for other technologies, and two terms can be used interchangeably about the same technology (e.g., additive manufacturing and 3D printing). The paper uses the foresight method horizon scanning to identify 133 technologies across all sectors of society. The technologies are presented on a list, which is sorted according to the number of sources that mention each technology. Using this ranking as a proxy for importance, the paper proposes that the following five technologies are the most important emerging technologies when preparing for disruptive changes: Internet of things, artificial intelligence, big data analytics, robots and blockchain. Short interviews with 25 technology-savvy stakeholders contributes to validating the list, as the most common technologies found in the horizon scan are also considered most important by the interviewees. Furthermore, the paper finds that most of the identified technologies are digital, and that only a few technologies on the list are targeted the construction sector (e.g., construction robots and prefabricated, volumetric construction).

Discussing the findings, the paper contends that the cross-sectoral approach facilitates an open-minded dialogue on the potential of new technologies in construction. Moreover, the paper proposes that the long-term-orientation of foresight methods, such as horizon scanning, is beneficial as it removes focus from current barriers to change in the construction sector. Finally, the paper proposes complementing the findings of the exploratory, technology-driven horizon scan, with an issue-centred, market-oriented foresight approach.

5.3 The Vision Paper: Identifying three potential futures of construction

This paper is found in Appendix C. The Vision Paper explores how digital technologies can be expected to affect the future of construction. The paper recognises that innovation champions play an important role in shaping the future of construction, as they are critical drivers of innovation in the sector. Through interviews with 13 innovation champions, the paper identifies three narrative visions of the future. The visions represent different narratives on how technologies and trends will affect the construction sector. The three visions are:

1) *Efficient construction:* This vision focuses on reducing time and cost of construction. The vision highlights the importance of optimising current work processes, e.g. through standardisation and strategic alliances. Key technologies include BIM, design automation tools, and modular, off-site construction techniques.
2) *User-data-driven built environment*: This vision focuses on enhancing the performance of the built environment. The vision highlights the importance of engaging the user in the design process and exploiting usage data throughout construction projects. Key technologies include big data, internet of things, and virtual and augmented reality.
3) *Value-based computational design*: This vision focuses on creating construction designs, which are customised to fit the context. The vision highlights the potential benefits of completely rethinking industry structures to focus on value-creation. Key technologies include design simulation, digital fabrication on-site and blockchain.

The three visions are visualised in a network graph that shows how multiple technologies and trends are interconnected and interdependent. The paper describes how the three visions are partially aligned with current technology, business and policy discourses of the sector, which suggests that innovation champions' narratives of the future influence – and is influenced by - broader sectorial discourses. The paper contends that our (sometimes unspoken) narratives of the future affects our present-day strategic choices, and correspondingly, it recommends that construction stakeholders clarify which future(s), they are aiming for. Finally, the paper proposes that construction stakeholders use the three visions as a frame of reference in dialogues that explore multiple possible futures and avoid striving for consensus on what the future will bring.

5.4 The Technology Cards Paper: Presenting a design game to navigate in digitalisation

This paper is found in Appendix D. The Technology Cards Paper is motivated by a desire to aid established construction companies in preparing for disruption. The paper describes the selection of 22 technologies that considered important for the construction sector. These technologies are concrete, domain relevant, demonstrated applicable in construction and possess a game-changing potential to the construction sector. Moreover, all but one of the selected technologies are digital: *Advanced building materials; Artificial intelligence predictions; Augmented reality; Autonomous construction vehicles; Big data analytics; Blockchain; Building information modelling (BIM); 4D, 5D and 6D BIM; Cloud-based construction management; Construction 3D printing; Construction robots; Drone survey; Generative design; Industrial* *exoskeletons; Intelligent buildings; Linked data for buildings; New building materials; Prefabrication and modular construction; Reality capture; Smart cities; Smart construction site;* and *Virtual reality*.

Each of the technologies are presented on a *Technology Card*, and collectively the 22 *Technology Cards* (and a few additional cards) constitute a card-based design game. The paper reports on the qualitative findings from testing the *Technology Cards* in 17 *Tech session* workshops with 257 participants. By framing the *Technologies Cards* as instruments of inquiry, the paper finds that the design game:

- Frame the perception of current challenges
- Explore how multiple technologies affect the future
- Identify interdependencies and synergies between technologies
- Engage stakeholders in constructive dialogues

The paper reviews 14 existing technology- and future-oriented design games and finds that these games primarily focus on the benefits of a specific new technology, or, anticipate the future without considering the effects of technology. In contrast, the *Technology Cards* bring attention to the combined potential of multiple technologies developing in parallel. Moreover, the paper finds that the game-like format of the *Technology Cards* encourages multiple stakeholders to contribute to future-oriented dialogues, regardless of their prior knowledge of technology. All in all, the paper connects the research fields of future studies and design and demonstrates that the *Technology Cards* are useful for facilitating future-oriented, strategic dialogues on the potential of new technologies. The *Technology Cards* are found in Appendix E.

5.5 Chapter summary

This chapter summarised the core insights from four papers:

- The Disruption Paper (Appendix A)
- The Horizon Scan Paper (Appendix B)
- The Vision Paper (Appendix C)
- The Technology Cards Paper (Appendix D and E)

6. Discussion

As digital technologies enter the construction sector, the threat of disruptive changes is evident. This thesis explores the future of construction through four studies focusing on: understanding the phenomenon of disruption, discovering potentially disruptive technologies, exploring digital futures, and facilitating action. The four studies are documented in four papers, that constitute the main body of this thesis: the Disruption Paper, the Horizon Scan Paper. the Vision Paper and the Technology Cards Paper. This chapter draws on the findings from the four papers to answer the five research questions, which motivated the thesis. Moreover, I propose implications to theory and practice, outline limitations of the thesis and point out directions for further research.

6.1 Answering the supplementary research questions

The four papers contribute to answering the overall research question of the thesis by providing answers to one or more of the supplementary research questions (see Table 3). In the following, I start by answering each of the supplementary research question before using these insights to answer the overall research question of the thesis.

Table 3: The four papers contribute to answering the four supplementary research questions

		DISRUPTION PAPER	HORIZON SCAN PAPER	VISION PAPER	TECHNOLOGY CARDS PAPER
RQ2	How can theory-based perspectives on disruption aid construction companies in anticipating future change?	●			
RQ3	Which technologies are potentially disruptive to construction?	●	●	●	●
RQ4	How might digitalisation affect the future of construction?			●	
RQ5	How can established construction companies prepare for the potentially disruptive effects of new technologies?	●	●	●	●

6.1.1 Research question 2: applying disruption theory to construction

Research question 2 investigates the applicability of disruption theory to construction:

How can theory-based perspectives on disruption aid construction companies in anticipating future change?

This research question is primarily answered by the Disruption Paper, which analyses *what* makes construction ripe for disruption, *when* disruption would likely occur, and *how* it may manifest. The Disruption Paper applies a Christensen perspective on disruption, and correspondingly, it focuses on anticipating demand-side disruption. In the following, I complement the findings of the Disruption Paper with the perspective on disruption by Gans (2016a), which contributes with a focus on supply-side disruption.

Predicting disruption

Various industries have been declared ripe for disruption. But little research has engaged in defining the term ‘ripe for disruption’ (Yu and Hang 2010). Does it mean that disruption is desirable - or inevitable? According to Christensen, Waldeck, & Fogg (2017), high costs and uneven access to offerings are typical characteristics of an industry that is ripe for disruption. According to Gans (2016a), industries are usually declared ripe for disruption because of noticeable inefficiencies, especially when considering current technological possibilities. Both these accounts of ‘ripeness’ characterises disruption as a *possible* – or perhaps even *desirable* – way of obtaining a greater level of performance of an industry. And correspondingly, I argue that disruption is *not* inevitable.

The Disruption Paper supports this arguments, as it finds that theory cannot prescribe if and when disruption will occur. If we imagine that we *could* predict demand-side disruption, this would entail that we mapped the performance trajectory of a promising disruptive innovation and compared it to the ‘demand trajectory’ of mainstream customers. In theory, disruption occurs when mainstream customers begin adopting a disruptive innovation in volume, i.e., when the two trajectories intersect (Christensen et al. 2015). However, in practice, drawing these trajectories is very difficult and leads to several questions, e.g. 1) how do we select the most important performance parameter of a disruptive innovation (Danneels 2004)? and 2) who are the mainstream customers and how do we map their demand trajectory? (I will return to this point of customer segmentation in the following). Building on these reflections from the Disruption Paper, I argue that predicting disruption is a very difficult, if not impossible, task.

Research has criticised the disruption theory’s inability to predict disruption ex-ante (Danneels 2004). In contrast to this critique, I propose that an indeterministic perspective on the disruption phenomenon is beneficial, as it emphasises that the future is uncertain. Moreover, this perspective highlights that the response of established companies to a disruptive change is crucial for whether disruption will occur or not (Gans 2016a). Correspondingly, I propose that established companies use disruption theory to explore various possible futures and responses.

Using the lens of disruption to explore possible futures

The Disruption Paper proposes that certain recommendations from disruption theory can help explore how disruption will manifest. This sub-section revisits the four recommendations from demand-side disruption literature:

1) *Invest early:* Disruption literature recommends that established companies should invest in disruptive technology at an early stage and create an independent organisational unit to mature the technology (Christensen 1997). While a first mover advantage may be beneficial in other sectors, research on construction innovation suggests that in construction coordinated actions are preferable to individual first moves (Taylor and Levitt 2004). In construction, multiple stakeholders, tasks and technologies are entangled in a complex network, which makes it difficult to anticipate the implications of implementing a new technology. This may be especially true for technologies that introduce systemic innovations, which affect several parts of the value chain.

2) *Identify non-consumers:* Disruption theory recommends that established companies look for new ways of engaging current non-consumers (Christensen and Raynor 2003). Transferring this recommendation to a construction context, the Disruption Paper suggest that new technologies can empower new stakeholder groups, such as neighbours or future users, to contribute to construction projects.
3) *Identify over-served customers:* Disruption literature recommends that established companies use customer segmentation to identify currently over-served customer (Christensen and Raynor 2003). To identify a disruptive innovation entering construction, it would arguable be useful to divide the market into low-end, mainstream and high-end customer segments as theory prescribes. However, customer segmentation is very rarely conducted in construction, neither by researchers nor practitioners (Mokhtariani et al. 2017). In fact, a review by Mokhtariani et al. (2017) found only one study that looks at customer segmentation in construction. There may be several reasons to why customer segmentation is difficult – or unproductive – in construction. Here I propose two:
    - The price of a construction product or service is typically settled in a bidding process, where various companies compete on price. Correspondingly, one could argue that most (if not all) construction customers are low-end customers.
    - The construction product or service is not a commodity, rather it is highly tailored to the individual customer. Correspondingly, the construction companies prefer to consider each customer to be a market-of-one, rather than grouping several different customers into one segment (Gilmore and Pine 2000).

   To sum up, it appears unproductive to discover disruptive innovations by observing the behaviour of low-end customers of construction. A more promising approach for discovering disruptive innovations entails looking out for new innovations that offer affordable and more convenient ways of delivering construction products and services. I propose that digital technologies play a central role in this, as they do indeed offer simpler and more convenient ways of working.
4) *Focus on value creation:* Disruption literature recommends that sectoral incentive structures are revised to focus on value creation (Christensen et al. 2017). This recommendation can be transferred directly to a construction context, where most contractual structures entail a mismatch between risk and reward. Disruption of the sectoral incentive structures may for example entail that the long-term value of a construction project (e.g. in terms of environmental impact or indoor work environment) becomes more important to the clients than the short-termed capital investment.

Common for all four recommendations are that they are proactive responses to disruption. Both demand- and supply-side disruption literature agrees that in the face of disruption proactive management is preferable to reactive (Gans and Kaplan 2017). Correspondingly, this thesis focuses on the potential benefits of using foresight to explore the implications of disruption on the future of construction.

6.1.2 Research question 3: Identifying technologies

The third research question investigates concrete technologies that may disrupt the construction sector:

Which technologies are potentially disruptive to construction?

As described in chapter 3.1.2, it is not the intrinsic characteristics of a technology, that makes a technology disruptive. Correspondingly, I do not propose that certain technologies are, in fact, disruptive technologies. Instead I use the phrase 'potentially disruptive' to signify that the technologies may trigger disruption, but that multiple factors – including the response of established companies – will determine if the mentioned technologies are indeed disruptive.

The Disruption Paper proposed that BIM is a critical driver of disruption, as it entails digitalisation of construction data which in turn enables other digital construction technologies. Furthermore, the paper suggests that automated construction technologies, such as robotics and 3D printing, may create disruption, as they change the way in which buildings are designed, constructed and operated.

The Horizon Scan paper identified 133 technologies from across sectors of society, and presented them on a list. Sorting the list according to the number of sources that mention each technology, the paper found that the following 15 technologies were the most common: Internet of things, artificial intelligence, big data analytics, robots, blockchain, virtual reality, additive manufacturing, autonomous vehicles, deep learning algorithm, machine learning, augmented reality, voice control, cloud computing, mobile connectivity and drones. As some technologies are umbrella terms for other technologies, we sometimes combined notions of similar technologies to create the list. If we were to repeat the Horizon Scan study, we would presumable define and combine the technologies differently. For example, we might choose to combine the technologies artificial intelligence, deep learning algorithm and machine learning into one technology, because of their significant overlap. However, despite the limitations connected to juxtaposing several technologies, I propose that the list provides a good source of inspiration for identifying potentially disruptive technologies. The majority of technologies found in the horizon scanning – and all of the 15 most commonly found technologies – are digital. This indicates that digital technologies are indeed found across all sectors of society and it suggests that digital technologies do indeed play an important role in shaping the future.

The Vision Paper explored the effect of digitalisation on the future of construction. Through interviews with 13 innovation champions, this paper identified important 17 technologies. These technologies are: artificial intelligence; augmented reality on-site and maintenance; big data; blockchain; building information modelling; connected autonomous vehicles and tunnels; design automation; design simulations; digital fabrication on-site; digital twin of city; distributed off-site production; future materials; internet of things asset management; internet of things energy consumption; modularisation; off-site construction; virtual reality and immersive design. The Vision Paper describes how these technologies are connected and interdependent, and contribute to different narratives of construction futures.

As evident from the all the three first papers, it is challenging single out a number of specific technologies as *the* most important technologies to consider, when striving to prepare for disruption. Nevertheless, the Technology Cards Paper attempts to do exactly this. Through an iterative design process that included both academic literature and practical experiences, the paper develops four criteria for selecting important technologies. The findings of the Technology Cards Paper suggest that a fifths criteria may be added, namely whether a specific technology is digital or not. This criteria aligns with the findings from the Horizon Scan Paper and the Vision Paper, both of which found that digitalisation is an important driver of progress. To sum up, the following five selection criteria may be worth considering, when a company searches for potentially disruptive technologies:

- *domain relevance*, i.e. ability to replace existing products and services
- *demonstrated applicability* within the sector
- *game-changing potential* to the sector
- *concrete* rather than abstract umbrella term
- *digital*, either partially or fully

Keeping in mind that technologies constantly evolve and change over time, I propose that this list of selection criteria can be a useful tool for continuous identification of potentially disruptive technologies.

The Technology Cards Paper present 22 potentially disruptive technologies that are important to the construction sector. As shown in Table 4, 18 of the 22 technologies are also identified in the Horizon Scan, and 12 are also identified in the Vision Paper. This suggests that established companies can make use of various different approaches to identify potentially disruptive technologies.Comparing the cross-sectoral approach described in the Horizon Scan Paper, and the domain-specific approach described in the Technology Cards Paper, I find that the domain-specific technology identification method returns the most useful results. Although the long list of technologies identified in the Horizon Scan Paper facilitates open-minded discussions about emerging technologies, the list does not aid strategic decision making in construction. In comparison, the list of technologies identified in the Technology Cards Paper is shorter, and the technologies are more easily relatable to a construction sector context. This insight illustrates that even though digital technologies possess the ability to cross sectorial boundaries, the application context is relevant for assessing technological potential. For generic technologies, which are partly physical (e.g., robots), it may seem obvious that the technology needs to be tailored to a specific context to provide value here. However, for fully digital technologies (i.e. big data), I suggest that the same conditions apply: the contextual application of a technology is important for evaluating its technological potential.

When assessing a list of technologies as the one in Table 4, and the one presented in the Horizon Scan paper, it is appealing to sort the list according to the number of times a technology is mentioned across sources. In this way, the count becomes a proxy for importance of the listed technologies, and it becomes easier to identify technologies that one might consider ‘inevitable’. However, if using the count as a proxy for importance, some limitations apply:

- *Hype* technologies are more likely to be placed in the top of the list, than more mature technologies. The public hype of a technology reflects that people are enthusiastic about its potential, while the technology is still immature.
- The more *abstract* terms of technology, such as internet of things, are likely to be placed on the top of the list, whereas specific applications, such as smart construction site, are likely to be placed further down on the list.
- The more *recent* technologies, such as reality capture, are likely to be placed further down on the list, whereas more mature technologies, such as building information modelling, are more likely to be mentioned by multiple sources.

As described in chapter 2.2, technologies constantly evolve, overlap and intersect. This makes it difficult to define a technology, to distinguish one technology from another, and to compare several technologies from an equal point of view. Correspondingly, I do not propose that the above list of 22 are the only 22 technologies that can be disruptive to construction. However, I do propose that the list of technologies provides a comprehensive snapshot of which technologies that are important to consider, when preparing for disruption of construction.

Table 4: 22 technologies that are potentially disruptive for the construction sector

	DISRUPTION PAPER	HORIZON SCAN PAPER	VISION PAPER	TECHNOLOGY CARDS PAPER
Agent-based modelling and discrete event simulations[1]		○	●	●
Artificial intelligence predictions		●	●	●
Augmented reality		●	●	●
Autonomous construction vehicles		●	●	●
Big data analytics		●	●	●
Blockchain		●	●	●
Building information modelling (BIM)	●	●	●	●
4D, 5D and 6D BIM				●
Cloud-based construction management[2]		○		●
Construction 3D printing[3]	●	●	○	●
Construction robots[3]	●	●	○	●
Drone survey		●		●
Generative design		●		●
Industrial exoskeletons		●		●
Intelligent buildings		●		●
Linked data for buildings				●
New building materials		●	●	●
Prefabrication and modular construction		●	●	●
Reality capture				●
Smart cities		●		●
Smart construction site				●
Virtual reality		●	●	●

Note: 1) This technology is referred to as 'modelling simulation and gaming' in the Horizon Scan Paper and 'design simulation' in the Vision Paper. 2) This technology is called 'cloud computing' in the Horizon Scan Paper. 3) These two technologies are referred to by the notion of 'digital fabrication on-site' in the Vision Paper.

6.1.3 Research question 4: exploring possible futures

The fourth research question focuses on exploring how the future of construction may look like:

How might digitalisation affect the future of construction?

Acknowledging that the future is uncertain, I propose that construction stakeholders can benefit from exploring multiple, different, possible futures. The Vision Paper outlines three narrative visions for the future of construction, which were discovered through interviews with innovation champions in the sector. Although the visions put emphasis on different technologies and trends, all three narrative futures highlight on the role of *digital* technologies. In the following, I provide a brief summary of the three visions, focusing on the role of digital technology. See the Vision Paper for a detailed account of each vision.

Vision 1, *efficient construction*, focuses on improving efficiency and reducing cost of construction. This future vision highlights digital technologies such as BIM, design automation and off-site construction, which can enable faster and more smooth construction work processes. Moreover, this vision focuses on reducing complexity of construction by means of standardisation and modularisation.

Vision 2, *user-data-driven built environment*, focuses on enhancing the performance of construction assets. This future vision highlights digital technologies that enable the collection of user data. This may be technologies such as internet of things or virtual reality that may be used for understanding how users interact with the built environment. Moreover, this vision focuses on enhancing sustainability and optimising the long-term value of the built environment.

Vision 3, *value-based computational design*, focuses on designing construction products that are customised to fit the context. This vision emphasises the ability of digital technologies to handle the inherent complexity of construction projects. This may be technologies such as design simulation software and digital on-site fabrication methods. Moreover, this vision entails restructuring the construction sector to facilitate data-driven and flexible construction projects.

As described in the Vision Paper, the three visions emphasise different phases of a construction project. Vision 1 focuses on the construction phase, vision 2 on the operation phase, and vision 3 on the design phase. Correspondingly, one could expect that companies concerned with the design phase (e.g., engineering consultancies) primarily commit to vision 3, while companies concerned with the construction phase (e.g., contractors) primarily commit to vision 1, and companies concerned with the operation phase (e.g., facility management companies) primarily commit to vision 2. However, the paper cannot find any correlation between the interviewees' company type and the interviewees' description of a vision. While further research is necessary to confirm such a conclusion, this finding indicates that prevailing narratives on the future of construction develop independently from the current organisation of the sector. Keeping in mind that the future is affected by our expectations for the future, this finding suggests that the future organisation of the construction sector will differ from the current suboptimal industrial structures.

As was also described in the Vision Paper, established construction companies may be tempted to combine the three visions into one narrative of how the future of construction will be. However, as multiple other possible futures exist, this is not a recommended approach. Instead, I propose that established companies acknowledge the indeterminable nature of the future and explore the differences between different possible futures. Which aspects of the future are interconnected and which aspects are interdependent? Which elements seem inevitable, and which elements may be negotiable? Such explorative discussions can help concretise the future, and contextualise the implications of present-day decisions. I therefore propose that future-oriented discussions are vital to prepare a company for possible disruption.

6.1.4 Research question 5: responding to disruption

The fifths research question is action-oriented as it strives to provide recommendations for established construction companies that prepare for disruption:

How can established construction companies prepare for the potentially disruptive effects of new technologies?

Both demand-side and supply-side disruption literature recommend established companies to respond proactively to the threat of disruption (Gans and Kaplan 2017). All four studies in this thesis support this theory-based recommendation as they demonstrate the benefits of using foresight methods to anticipate disruptive change.

The Horizon Scan Paper revealed that a cross-sectoral approach for technology identification facilitated an open-minded dialogue on the potential of emerging technologies. However, the paper also found that only a few of the identified technologies were targeted construction. Correspondingly, I recommend that established companies apply a domain-specific approach to identify potentially disruptive technologies.

The Vision Paper recommends that established companies anticipate the implications of digitalisation by exploring multiple possible futures. The paper finds that practitioners' expectations for the future are reflected in current discourses on technology, business and policy in the sector. To identify several possible futures, established companies may therefore benefit from looking actively for counter-discourses on how the future will unfold. Furthermore, the Vision Paper recommends that established companies are aware of how their conscious - or unconscious - narratives of the future affect their present-day strategic choices. Ideally, a construction company should be able to connect their present-day technology investment decisions to their strategic aims for the future. In practice, this process may entail that companies engage in selecting a preferred future (among multiple possible futures), and then use backcasting to identify and prioritise the steps necessary to obtain this preferred future. As described in the Technology Cards Paper, the game-like nature of the *Technology Cards* helps facilitate this future-oriented strategic process. The Technology Cards Paper recommends that multiple stakeholders are involved in future-oriented dialogues on the potential of digital technologies. By including stakeholders that do not possess in-depth knowledge about new technologies, established companies ensure that other concerns (such as user needs and environmental concerns) are considered at an equal standpoint to that of technology. Moreover, I propose that by involving multiple stakeholders in envisioning the future, companies can create a shared perception of impending changes across the organisation. Such a shared perception of the future is beneficial, as it leads the way for innovation. Correspondingly, I propose that by involving multiple stakeholders in envisioning the future, the construction sector can encourage that innovation is driven, not only by innovation champions, but by multiple stakeholders from different backgrounds.

Both the Technology Cards Paper and the Vision Paper found that by considering multiple technologies in combination, synergies arise. Correspondingly, I propose that established companies may prepare for disruptive changes by considering the combined impact of multiple technologies.

Across all four studies, I find that the long-term orientation of foresight methods remove attention from the action-inhibiting challenges that dominate the construction sector. Correspondingly, I propose that long-term oriented foresight methods can help construction companies overcoming barriers to change and preparing for a future of possible disruption.

6.2 Answering the main research question

The overarching research question of this thesis reads:

RQ1: How might digital technologies disrupt the construction sector and what can established construction companies do about it?

The first half of this question explores the potentially disruptive implications of digital technologies to construction, while the second half searches for recommended responses to disruption. In the following, I synthesise the insights from the four papers to answer both halves of the overarching research question.

6.2.1 How digital technologies might disrupt construction

Drawing on the findings from the four papers, I propose that digital technologies are especially powerful triggers of disruption. As digital technologies build on generic building blocks (i.e. binary digits), these technologies possess boundary-spanning capabilities. By means of digital technology, information can cross geographical boundaries (e.g., by transferring data to another country in a second), domain-related boundaries (e.g., by combining data from multiple sources to inform traffic planning) and task-dependency boundaries (e.g., by sharing and accessing data from multiple places at once). The boundary-spanning capabilities of digital technologies entail that these technologies diffuse through all sectors of society – also in construction.

The four papers found that technologies and trends interconnect and interdependent, as they affect the future. The Vision Paper presents three ways in which digital technologies may affect the construction sector in the future (as summarised in chapter 5.3 and 6.1.3). In the following, I complement the three visions with reflections on whether the visions anticipate disruption of construction.

Vision 1 aims to improve time and cost of construction. Both of these performance parameters dominate the construction sector today. Referring to Christensen's original of disruption, which states that disruptive technologies change the parameters of performance in a market, I find that Vision 1 anticipates no disruption of construction, and correspondingly, one of the future aspects forming vision 1 is called "no disruption". Instead, this vision focuses on streamlining work processes in the construction value chain and improving contractual structures between (already existing) construction companies. Although vision 1 also entails some large-scale changes to the sector, e.g. through the implementation of off-site construction, these changes are not likely to characterise as disruption, as they do not appear to rearrange the way knowledge is structured in the sector (supply-side disruption), or offer a new value proposition to customers (demand-side disruption).

In contrast to vision 1, vision 3 anticipates large-scale changes to the stakeholder network and industrial structures of construction. This vision illustrates how supply-side disruption may manifest in construction, as it describes how construction professionals will be hired for project-based, temporary positions and organised in networks rather than in corporate companies as today. The vision also describes how construction production facilities will be moved to distributed, off-site locations, hereby entailing changes to the value chain. The anticipated changes to the flow of data, materials and people in the sector induce large-scale changes to the architectural knowledge of established construction companies, and correspondingly, supply-side disruption is likely. If vision 3 is realised in practice, established companies may find it difficult to respond appropriately, sufficiently and timely to avoid being disrupted.

Conveniently, vision 2 can be used to illustrate how demand-side disruption may manifest in construction. As described in the Disruption Paper, demand-side disruptive innovation can be identified through an analysis of customers' jobs-to-be-done, asking e.g. "Why do construction clients invest in a construction project – what outcome is the client trying to achieve?" For example, the job-to-be-done of a construction client may be reformulated from "building a new headquarter" to "ensuring that my employees can work productively by providing a good indoor working environment". If construction companies commit to this reframing of their value proposition, the outcome of a construction project should not be measured in terms of money or time, but rather in terms of e.g. well-being of the users. Correspondingly, vision 2 focuses on the well-being of users of the built environment. This vision emphasises how digital technologies, such as internet of things and virtual reality, can be used to harvest valuable user insights needed to optimise the operation of the built environment. Following the recommendations from demand-side disruption theory, established companies may benefit from investing in digital technologies from an early stage and offering affordable and convenient construction products,. which target end-users.

The three visions are exploratory by nature. They illustrate how disruption of construction is possible and maybe even desirable. And they illustrate how digital technologies seem to be an inevitable part of the future. However, the visions should not be considered accounts of the truth. Only time can tell, what the future holds – and the realised future may likely contain elements from all three visions. However, although the future is uncertain, the future is not impervious to our actions. Established construction companies should be aware of their ability to affect the future through their present-day strategic decisions. The following sub-section summarises how construction companies may respond to the threat of impending disruption.

6.2.2 How established companies can respond to disruption

The answer to research question 5 contribute to answering the second part of the overarching research question: "How might digital technologies disrupt the construction sector and what can established construction companies do about it?" Building on the insights from the answers to research question 5 (see chapter 6.1.4), this section synthesises the recommendations for established construction companies facing disruption:

- **Use foresight.** Disruption literature recommends established companies to act proactively with regards to disruption. This thesis demonstrates the potential benefits of using foresight methods to anticipate change.
- **Envision long-term futures.** The fragmented and complex industrial structures of construction inhibits sectoral innovation. The Technology Cards Paper demonstrates how long-term orientation can help construction stakeholders overcome the current barriers to change.
- **Consider multiple technologies.** Technologies and trends interdepend and interconnect. This thesis advocates for the benefits of assessing the implications of multiple, digital technologies in combination. The *Technology Cards* provides a straight-forward way to do so.
- **Explore several possible futures.** To investigate which aspects of the future that are negotiable and which aspects that seem inevitable, this thesis recommends established companies to explore several possible future scenarios.
- **Be aware of which future you are aiming for.** The future is affected by the present. This thesis proposes that established companies can benefit from articulating their preferences for the future, as this allows for their preferred future to affect present-day strategic decisions.
- **Involve stakeholders in future-oriented dialogues.** Several concerns affect the future. To avoid over-emphasising the effect of technologies on the future, established companies may benefit from involving stakeholders from various backgrounds in future-oriented dialogues, e.g. both technology-savvy and non-technology-savvy stakeholders. The *Technology Cards* provides an inclusive approach to do so.
- **Keep identifying potentially disruptive technologies.** Technologies evolve and change over time. This thesis proposes five selection criteria to guide the identification of relevant technologies. To ensure that established companies are constantly aware of potentially disruptive technologies, they are advised to ensure that technology identification activities are an integral part of their strategic management processes.

Summing up, digital technologies may trigger disruption of construction. To prepare for this, established construction companies can apply a number of strategies. This thesis advocates for the benefits of applying foresight methods to explore multiple, possible, long-term futures, which entail a combination of multiple technologies and trends. Moreover, the thesis proposes that established companies should be aware of their ability to affect the future. Concretely, the thesis recommends that established companies engage in future-oriented dialogues with multiple stakeholders from various backgrounds, e.g. through a design game such as the *Technology Cards*. These future-oriented dialogues may benefit from aiming at envisioning a preferred future and deciding on strategic actions to prepare for this future, including the potentially disruptive implications of digital technologies.

6.3 Implications for theory and practice

This thesis contributes to both theory and practice. In the following, I outline the implications for research on disruptive innovation and research on design and futures studies as well as the implications for construction practices.

6.3.1 Implications for research on disruptive innovation in construction

This thesis was motivated by a call for research on if and how disruption theory applies in a systemic industry like construction (Christensen et al. 2018). The thesis presented three theoretical perspectives on disruption and, through four exploratory studies, it investigated these perspectives' ability to anticipate change and provide recommendations relevant to a construction sector context.

Synthesising the insights from this thesis, I propose that the following theory-based recommendations from disruption literature are applicable in a construction sector context. To identify or create disruptive innovation, established companies should:

- Look for innovations that introduce affordable, simple and convenient alternatives to mainstream products (Christensen et al. 2018)
- Identify and target customers' actual jobs-to-be-done (Christensen and Raynor 2003).

Other aspects of disruption literature are less applicable in a construction context. Synthesising insights from the thesis, I propose that the following recommendations from disruption literature need to be adjusted to fit construction. Established construction companies should <u>not</u>:

- Invest in potentially disruptive technologies from an early stage, and create a separate organisational unit to mature the technology (Christensen 1997). In contrast, the implementation of game-changing technologies in construction appear to require coordinated effort from multiple stakeholders across the value chain. Correspondingly, I propose adjusting this theory-based recommendation to a construction context by advising established companies to engage in partnerships with other construction stakeholders aimed at developing promising technologies.
- Focus on identifying low-end or new-market customers (Christensen and Raynor 2003). In construction, the product is customised to each customer, and correspondingly, customer segmentation is difficult or unproductive.

Considering disruption in a construction context, I recommend committing to Gans' (2016a) perspective on disruption as a phenomenon that includes supply-side disruption. The notion of supply-side disruption resonates well within the construction sector, where the implementation of non-incremental innovation typically cross company boundaries and affect multiple parts of the value chain. Furthermore, I suggest connecting research on systemic innovation and disruptive innovation to explore the industry-changing potential of digital technologies.

6.3.2 Implications for design and futures studies research

This thesis connects futures studies and design research. As described in chapter 1.4. and 4.4, the fields of design and futures studies are similar and somewhat overlapping (Ollenburg 2019). Both fields apply participatory and interdisciplinary methods to study complex problems – either through anticipating the future, or through designing solutions to improve the future.

The thesis demonstrates the benefits from combining foresight and design methods. Foresight methods, such as horizon scanning and visioning, contributes to design as they consider the potential long-term advantages and challenges of implementing digital technologies. On the other hand, design methods, such as design games and workshops, contribute to futures studies as they make digital futures tangible and concrete to stakeholders. By engaging stakeholders in playful explorations of the future, the thesis combines foresight and design to make digital futures both visionary and tangible.

Moreover, the thesis demonstrates the benefits from framing the challenges of implementing digital technologies in construction as a design problem. Design can considered the co-evolution of problem and solution (Dorst and Cross 2001). Whereas much research on construction innovation focuses on explaining the current barriers to change (the problem), this thesis focuses on exploring how digital technologies may change construction (the solution). In this way, the thesis complements existing market-oriented research with a technology-oriented approach. Building on the insights from this thesis, I propose that when striving to anticipate the complex and unpredictable implications of digital technologies to society, a future-oriented design approach is suitable.

6.3.3 Implications for construction practices

While the game-changing effects of disruptive technologies are observable in a large number of sectors, the implications for the construction sector are not well described. Reading this thesis, construction practitioners may get a better sense of how disruption may play out in their sector and what they can do about it.

The thesis presents three digital visions for the future of construction, which can be used as frame of reference in sectoral discussion on utilising the benefits of digitalisation. In this way, the thesis complements sectoral innovation initiatives, e.g. the Molio Contech project in Denmark (Molio 2020b), and policy development discourses, e.g. the Transforming Construction agenda in the UK (HM Government 2018), as it nuances the future-oriented debate on digitalisation of construction.

A concrete outcome of this research project is the development of 22 *Technology Cards*, which presents some of the most important, potentially disruptive technologies to construction. Practitioners are encouraged to use the cards to facilitate strategic dialogues about the future of the sector.

6.4 Limitations and suggestions for further research

This thesis presents in-depth, qualitative insights into how digital technologies may affect the construction sector in the future. These insights are the result of exploratory research, and correspondingly, they are not conclusive. Rather, I propose that the insights and recommendations generated in this thesis form the basis for further research on the topic. Such research could e.g. explore the generalisability of the findings to another project-based and/or systemic industry, or investigate how digital technologies can help leverage the sustainability agenda in construction.

The thesis explores the phenomenon of disruption in construction from the point of view of established companies. Correspondingly, it focuses on *navigating in* a changing environment rather than on *creating* change. This point of view may affect the interpretation of data. Complementary research could explore disruption of construction from the point of view of potential disruptors. Such research could e.g. draw on business model innovation research (Osterwalder and Pigneur 2010) and propose different strategies for leveraging disruption in construction.

When expecting disruption, a proactive response is needed. The timing of such a response is vital. If established companies act too slow, they may be disrupted – and if they act too fast this may result in bigger losses due to cannibalisation of their existing products. Acknowledging that disruption cannot be predicted, further research may investigate how established companies can time their response to disruption. Such research may also combine disruptive innovation literature (Christensen and Raynor 2003) with systemic innovation literature (Taylor and Levitt 2004) to investigate whether the speed of diffusion of an innovation affects the likelihood of disruption.

This thesis focuses on the medium- and long-term futures of construction. While the exploratory insights of this thesis may be used to guide strategic planning in established construction companies, further work is needed to transform the strategic intentions to concrete actions. Further research may, for instance, use the three future visions presented in the Vision Paper to specify concrete steps necessary to implement digital technologies in construction. Such research may also identify potential pitfalls involved in the implementation of digital technologies, and use risk management to mitigate these risks.

This thesis investigates to which extent disruption can be used to anticipate the presumably game-changing implications of digital technologies to construction. However, multiple other conceptual notions may do the same. For example, the Vision Paper uses the term '*digital transformation'* to describe the anticipated changes triggered by digital technologies. This thesis describes how the notion of disruption entails a sense of urgency and a focus on the (proactive) actions of established companies. In contrast, the notion of digital transformation may emphasise that the implementation of digital technologies requires dedication and commitment for a longer period of time. Further research may shed light on the benefits and disadvantages of using another notion, such as digital transformation, to anticipate future changes in the construction sector.

6.5 Chapter summary

Building on the insights from the four papers, this chapter:

- Reflected on the applicability of disruption theory to a construction context (RQ2).
- Identified technologies that are potentially disruptive to construction (RQ3).
- Emphasised the technology aspect of the visions presented in the Vision Paper (RQ4)
- Developed recommendations for how established construction companies can prepare for disruption (RQ5 and the second half of RQ1)
- Connected the three visions to disruption theory, hereby outlining how disruption may unfold in construction (the first half of RQ1).
- Specified which recommendations from disruption theory that are relevant in a construction context and which that are less relevant.
- Described the implications of this research to design, futures studies and construction.
- Outlined limitations of the research and suggested topics for further research.

7. Conclusion

To help established construction companies realise the benefits of digital technologies, this thesis explored potentially disruptive futures of construction. The thesis built on four studies that describe theoretical principles of the disruption phenomenon, identify potentially disruptive technologies, outline three visions for a digital future of construction and design support to facilitate future-oriented strategic dialogues.

The thesis contributes to research by studying the applicability of disruption theory to the systemic industry of construction. Key takeaways include that construction companies should identify their customers' jobs-to-be-done and be aware of new entrants offering disruptive innovations that are cheaper, simpler and/or more accessible. The thesis proposes that other recommendations from disruption theory – concerning early technology investment and customer segmentation – are less feasible in a construction sector context. Moreover, the thesis documents the design of the *Technology Cards* design game, hereby demonstrating how a future-oriented design approach is well-suited for exploring the potential implications of digital technologies. By combining the playful elements of a design game with the long-term orientation of futures studies, the thesis demonstrates how digital futures can become both visionary and tangible to stakeholders.

The thesis contributes to construction practices by presenting concrete recommendations for realising the benefits of digital technologies and avoiding being disrupted. Established companies are advised to consider multiple possible futures and consider the combined impact of multiple technologies. Acknowledging that the realised future is affected by our expectations for it, the thesis furthermore recommends that multiple stakeholders from different backgrounds are involved in envisioning the future. The *Technology Cards* and the *Tech Session* concept can be used for engaging stakeholders in this strategic dialogue. By responding proactively and sufficiently, established companies can navigate disruptive changes and enhance their competitive ability. This will not only benefit the company, but also the construction sector in general and hereby society as a whole.

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Appendix A: The Disruption Paper

Ernstsen, S. K., Maier, A., Larsen, L. R., and Thuesen, C. (2018a). “Is construction ripe for disruption?” *Association of Researchers in Construction Management (ARCOM) - Proceedings of the 34th Annual Conference*.

IS CONSTRUCTION RIPE FOR DISRUPTION?

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The notion of 'disruption' and particularly that of 'disruptive innovation' is now widely used by researchers as well as management practitioners, and the construction industry is being described as 'ripe for disruption'. By comparing this industry to healthcare (another massive, societally important industry also considered ripe for disruption), this paper applies the lens of disruption theory to analyse the current and anticipated status of the construction industry. To do so, we ask and answer three central questions: Why should construction be ripe for disruption? When will disruption potentially occur? How will disruption likely manifest? We find that both industries share a number of challenges, including a fragmented stakeholder network, complex incentive structures and a sense of being in a deadlock that makes change difficult. Furthermore, we find that in both industries the term 'ripe for disruption' describes a process rather than prescribe when disruption will occur. By applying central notions from disruption theory (disruptive technologies, low-end disruption, new-market disruption, and a focus on value creation), we identify several potential disruptors of the construction industry. To conclude, we discuss the benefits and limitations of applying disruption theory to the construction industry.

Keywords: disruption theory, disruptive innovation, healthcare, industry comparison

INTRODUCTION

"Disrupt - or be disrupted" has become a common catchphrase of today. Managers and scholars alike seek to understand the nature and potential impact of disruptive innovation. In 2003, Charitou and Markides (2003) identified 14 examples of industries having experienced disruptive strategic innovations. The list included industries as diverse as the steel industry, the airline industry and the life insurance industry - and since then, more industries could arguably qualify for the list.

Observing how disruptive innovation has upended competition in other industries, the notion of disruption has also reached the construction industry. In recent years, two comprehensive analysis reports have described the construction industry as being ripe for disruption (World Economic Forum, 2016; McKinsey Global Institute, 2017). Similar conclusions are found in other recent grey literature such as Fortune (Tobak, 2016) and Disruptor Daily (Rands, 2017), both listing construction as one of three to six industries which soon will be disrupted. Arguably, disruption has become a popular buzzword that attracts the attention of business managers. However, the term also form the basis of scholarly theory (Christensen, 1997; Christensen and Raynor, 2003). In this paper, we

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will take the point of departure in the theory of disruption while seeking to answer the main research question: Is the construction industry indeed ripe for disruption?

Previous research has compared the construction industry's development, innovation and productivity to that of the manufacturing industry, as this industry has accomplished to benefit from several transformations during the last 100 years (Slaughter, 1998; Winch, 2003). However, this comparison is limited due to the distinctive features of construction, including a comprehensive regulatory environment, the need for on-site assembly, and long life expectancy requiring long-time testing (Slaughter, 1998). Consequently, Winch (2003) suggests learning from other industries that similarly to construction has a complex system production model, and Concept-to-Order (CtO) or Design-to-Order (DtO) production strategies.

The U.S healthcare sector is an example of such an industry. As we will show, this sector shares a number of characteristics with the construction industry - including a recent label of being 'ripe for disruption' (Christensen, Waldeck and Fogg, 2017). Seeking to understand whether construction is indeed ripe for disruption, we compare the two industries. The industry comparison is guided by three sub-questions:

- What makes us believe an industry is ripe for disruption - and in particular, why should construction be ripe for disruption?
- When will disruption potentially occur?
- How will disruption likely manifest?

We begin by reviewing the most important aspects of disruption theory. Next, we present the two industries and describe our method. The main body of the paper is shaped by the three questions above. For each question, we describe the status of the two industries separately, and identify similarities, differences and opportunities for learning. Finally, we discuss how disruption theory may contribute to construction and to which extent the construction industry can be characterised as ripe for disruption.

DISRUPTION THEORY

The notion of disruption has intrigued business managers and scholars, since it was coined by Bower and Christensen in 1995. Disruption occurs as new innovations "bring to market a very different value proposition than had been available previously" (Christensen, 1997, xv), hereby changing the bases of competition in a market (Danneels, 2004). The theory on disruption is based on multiple case studies of technological development in e.g. the disk drive industry and the steel mill market. In these cases, disruption occurred because well-managed, established companies failed to recognise the disruptive characteristics of new technologies before it was too late. Dealing with disruptive technologies, the theory thus emphasizes the importance of first mover advantage and recommends incumbent to invest in disruptive technologies while they are still relatively immature (Christensen, 1997). Christensen and Raynor (2003) differentiate between low-end and new-market disruption. Low-end disruption happens when a low-cost and low-performance disruptive offering enters an existing market, and eventually overtake mainstream customer segments, as the performance of the disruptive offering improves. Opposed to this, new-market disruption targets current non-consumers and creates a new value-network.

Reviewing disruption theory, Danneels (2004) and Markides (2006) emphasised the lack of a clear-cut definition of disruptive technology and disruptive innovation and question the theory's ability to make ex-ante predictions. Nonetheless, the notion of disruption has been used increasingly often in the last few decades (Christensen, Raynor and McDonald, 2015), leading to a rather diluted understanding of the term. Correspondingly, much research has investigated how disruption should be defined, and if and how disruption may be predicted (e.g. Danneels, 2004; Markides, 2006; Yu and Hang, 2010).

The term "ripe for disruption" is not as often found in research literature. However, according to Yu and Hang (2010), Schmidt (2004) proposed that a market is ripe for disruption if it is characterised by customers that are overserved according to traditional attributes, and underserved according to secondary attributes. Analysing the U.S healthcare sector, Christensen *et al*., (2017, 4) state that "High costs and uneven levels of access are typical hallmarks for an industry that is ripe for disruption". Consequently, we argue that to predict disruption we need to analyse the current status of an industry. Rather than focusing on specific technologies or a company setting, we will here apply the disruption lens in an industry context.

METHODOLOGY

The construction and healthcare are of course two very different industries. The main offerings of the healthcare system include diagnosing and treating patients, whereas the main offerings of construction are centred on designing and constructing physical structures. Where the primary outcome of healthcare is healthy people, the primary outcome of construction is a built environment. Despite their vast differences in offerings, the healthcare and construction industries share a number of characteristics. Both are quite large industries, given that each constitute 9-10 % of EU's gross domestic product (European Commission, 2016; Eurostat, 2016). The industries are of societal importance, depend on public investment, and have a complex ecosystem of actors with different roles, agendas and mandates. And perhaps most importantly, although both industries have been proclaimed ripe for disruption, both struggle with implementing disruptive changes at the same speed as other industries (World Economic Forum, 2016; Christensen, Waldeck and Fogg, 2017). The healthcare sector and the construction industry both score among the lowest when comparing the degree of digitalisation to other industries (Gandhi, Khanna and Ramaswamy, 2016), indicating that they experience a need for embracing the opportunities provided by new technologies and digital innovations.

We base the description of healthcare disruption on research material from the Christensen Institute (Christensen, Bohmer and Kenagy, 2000; Christensen, Waldeck and Fogg, 2017) as well as other academic articles on anticipated disruptive changes in the healthcare sector (e.g. Patou and Maier, 2017). The Christensen Institute analyses how disruption is happening in various industries with a special focus on the U.S healthcare sector. We will keep in mind that healthcare, like construction, is a very diverse industry on a global scale - and all the inherent mechanisms of the U.S healthcare sector may not be present in e.g. European equivalents.

The description on construction disruption is based on two rather recent industry analysis reports from McKinsey Global Institute (2017) and World Economic Forum (2016), and supplemented by academic articles on anticipated disruption of construction and construction innovation (e.g. Winch, 1998; Bock, 2015). We will consider construction as a global industry although we acknowledge that there are very large regional differences. We recognise that consultancy reports may be biased since consultancies arguably may benefit from claiming that an industry is ripe for disruption. However, the comprehensiveness of the analysis behind the reports as well as the anticipation of construction disruption from other, purely academic sources (e.g. Bock, 2015), make us include the reports as relevant sources.

Why Should Construction Be Ripe for Disruption?

Already in 2000, Christensen *et al*., proclaimed that the U.S healthcare sector was ripe for disruption. This conclusion is based on a description of the sector as highly expensive, resistant to innovation, competing fiercely on price and delivering low-quality offerings. Further describing the challenges of healthcare, Christensen *et al*., (2017) emphasized the high cost and uneven access to offerings as key reasons for why disruption should be anticipated.

McKinsey Global Institute (2017) describes construction as ripe for disruption based on a global analysis of the challenges and productivity of the industry. Based on studies of productivity in more than 30 industries, they argue that the productivity of construction is "remarkably poor" and could be improved by 50-60 percent. World Economic Forum (2016) argue that the large societal, economic and environmental impact of the construction industry makes the potential of digitally transforming the industry significant. They both point towards the opportunities in e.g. standardizing processes, rethinking contractual structures, changing regulations and adopting new technologies.

Although both industries have identified the need for change, they are described as in a sort of deadlock that makes change difficult. In both industries, a large barrier to change stems from the complex network of actors with different objectives. Moreover, fierce competition makes it challenging for a single actor to break the deadlock - at least not without close coordination with others. The challenges that are used to characterise the industries as ripe for disruption are summarized in Table 1.

Table 1: Challenges used to characterise construction and healthcare as ripe for disruption

	Construction	U.S healthcare
Stakeholder network	Industry opaque and highly fragmented.	Powerful stakeholders interested in maintaining status-quo.
Incentive structures	Tenders or invoices according to time spent. Contractual structures and incentives misaligned.	Fee-for-service model. Difficult to calculate profitability per procedure. Focus on utilisation of assets.
Market dynamics	Fierce competition, slim margins. Informality and potential for corruption. Sub-optimal owner requirements.	Fierce competition between old institutions on price and accessibility. Uneven access to healthcare.
Quality of offerings	Poor project management and execution. Megaprojects surpass time and budget.	Reduced quality due to time pressure. This is dissatisfying to patients.
Skills vs. tasks	Low skill-level of workers. Need for training workers to use the latest equipment and digital tools.	High skill-level of doctors surpass most patients' needs.
Investment	Low degree of investment in digitalization and innovation.	Investments focus on treating difficult high-end diseases.

Although disruption theory does not provide specific parameters for assessing whether an industry is ripe for disruption, our comparison suggests six parameters that may characterise an industry as ripe for disruption. Moreover, it is shown that construction and healthcare experience quite similar challenges according to most parameters. The only major difference is the skill-level of professionals, which is claimed to be too low in construction and too high in healthcare.

Besides having similar challenges, both industries report that they experience that other industries have succeeded in benefiting more from a digital transformation, than they have (World Economic Forum, 2016; Christensen, Waldeck and Fogg, 2017; McKinsey Global Institute, 2017). Thus, disruption is anticipated due to an experience of missed opportunities rather than because current challenges constitute a burning platform.

When Will Disruption Potentially Occur?

The proclamation of a need for change in the construction industry is not new. Already in the late 1930s, Schumpeter argued that prefabricated housing would bring a "gale of creative destruction" to the construction industry, in the same way as mass production changed other industries (Winch, 1998). Winch (1998) argues that Schumpeter was wrong and that the industry has not yet experienced the cost reduction and quality improvements seen in other industries in last 100 years. So why should disruption occur in the construction industry just now?

A similar question is asked in the healthcare sector, where 17 years have passed since the sector was first described as ripe for disruption. Christensen *et al*., (2017) suggest that characteristics of U.S healthcare make the sector impervious to change: End-users (i.e. patients) lack control of the design and buying decisions, new competitors experience high barriers to entry, and the fee-for-service reimbursement system fails to consider the quality of the care. Despite these forces repelling disruption, they persist in concluding that healthcare will be disrupted, although slower than initially expected.

In theory, disruption occurs at that exact point in time when the performance of a disruptive innovation surpasses the performance of mainstream offerings (Christensen, 1997). Thus, by mapping the performance trajectory of an expected disruptive innovation as well as mainstream offerings, one should be able to anticipate when disruption will occur. In practice, however, it is challenging to determine the disruption point before disruption has actually occurred (Danneels, 2004). One reason for this is that performance may be measured according to many different parameters - and that choosing the right parameter is not trivial. For example, for a group of customers in the construction industry the most important performance parameter could be "time from idea to finished building" or "life-time cost" or (most likely) something else. Even if one has identified the most important performance parameter for mainstream customers today, one should keep in mind that disruption may imply that this parameter is not the most important for customers tomorrow.

Thus, seeking to predict when disruption will occur in construction and healthcare is challenging. However, assuming that disruption will occur at some point, the challenge may be worth undertaking for construction companies to avoid being surprised by disruptors. Acknowledging the limitations of predicting the future, we believe companies in the construction industry may benefit from using e.g. foresight methods to identify potential disruptors. In the following, we identify some of the potentially disruptive technologies and innovations that should be analysed to be able to estimate when disruption could occur in construction.

How Will Disruption Likely Manifest?

To understand how disruption may be anticipated in construction, we will take point of departure in four recommendations found in disruption theory:

- Disruptive technologies: Invest early as a first mover advantage is essential
- Low-end disruption: Identify overserved customers
- New-market disruption: Identify current non-consumers
- Focus on creating value for the customer

Disruptive technologies: Invest early as a first mover advantage is essential
Technological progress is often brought forward as a reason to anticipate disruption. However, in the analyses of healthcare disruption, new technologies are merely mentioned as an enabler of disruption, alongside with new innovative business models and a changed value network (Christensen, Waldeck and Fogg, 2017).

According to McKinsey Global Institute (2017), the largest potential for productivity improvement of the construction industry stem from the implementation of new technologies. Especially the anticipated disruptive potential of Building Information Modelling (BIM) has long been studied by construction researchers (e.g. Morgan, 2017). World Economic Forum (2016) conducted a survey about the perceived potential of construction technologies among industry experts, and here integrated BIM was rated as extremely likely and anticipated to have an extremely high impact. BIM is arguably a critical driver of disruption in construction since digitalisation of data makes several other new value propositions possible. Another important group of potentially disruptive technologies is found in automated construction technologies such as 3D printing and construction robotics (Bock, 2015). Bock (2015) argues that automated construction technologies will speed up construction processes, change the way buildings are designed, and eventually pervasive robotics (e.g. service robots) will be an integrated part of the built environment. Considering these examples of technological progress in both the virtual and physical dimensions of construction, we expect disruptive changes to affect the entire value-chain of construction.

When companies have identified supposedly disruptive technologies, they should, according to theory, act as first movers in maturing the technologies to avoid being disrupted. This recommendation, however, contrasts the description of construction and healthcare as being in a deadlock where stakeholders need to act simultaneous for change to occur. In construction, for example, multiple companies have invested heavily in BIM to gain a first mover advantage. However, BIM seems to gain grounds through a coordinated effort (including legislative action) rather than through a strategic first move. As disruption theory focuses on the actions of a single company, it does not provide recommendations for coordinating disruptive initiatives across an industry.

Low-end disruption: Identifying over-served customers
According to disruption theory, incumbent companies may prepare for disruption by identifying current customers that are currently over-served. Christensen *et al*., (2017) argue that on one hand, the U.S healthcare system delivers dissatisfying services to patients due to e.g. time constraints on consultations. On the other hand, the healthcare offerings overshoot the needs of the majority of patients, as highly educated doctors attend all patients without differentiating between minor and major health issues. Thus, the recommendations for healthcare include creating a system where the skill level of the health professional corresponds to the difficulty of the medical issue (Christensen, Bohmer and Kenagy, 2000).

Translating this line of thoughts to construction, we find that construction, like healthcare, defines its offerings based on professional disciplines rather than complexity of the offerings. For example, larger companies in the construction industry are typically differentiated by profession (e.g. architect or engineer) rather than by the nature of assignments (e.g. school building or landscape planning). In this regard, disruption theory recommends taking the point of departure in the customers' jobs to be done and look for over-served customers. Over-served customers may be customers that currently buy relatively low-cost offerings (e.g. expansions of an office building) without actually needing the high-end offerings that the company is capable of providing (e.g. specialised knowledge used for designing hospitals).

An example of a low-end disruptor of construction is Altan.dk, a specialized company that delivers customized balconies including customer service, installation and life-time support (Kudsk *et al*., 2013). Altan.dk has succeeded in identifying a customer group that needs "only" the services related to designing and establishing balconies on existing buildings. Although the balconies are customized, they are designed using a product configuration system of standardised components, enabling Altan.dk to deliver a low-cost product that is valuable to a specific group of customers.

As the case of Altan.dk demonstrates, low-end disruption of construction does happen. Disruption theory may therefore contribute to construction through its emphasis on the (often over-looked) potential of low-cost, low-performance offerings that improve over time. Correspondingly, construction companies may benefit from identifying low complexity tasks that 1) could be bundled as a low-cost offering, and 2) may develop to a high-end product over time as technology improves.

New-market disruption: Identifying current non-consumers

Another type of disruption, which might be anticipated in construction, is new-market disruption. According to theory, this kind of disruption may be found by identifying current non-consumers. An example from healthcare is that of doctors prescribing patients to change their lifestyle, e.g. exercising more, losing weight and/or eating healthier to prevent e.g. diabetes or depression (Christensen, Waldeck and Fogg, 2017). These patients can be seen as non-consumers since they are expected to make lifestyle changes between the occasional doctor's appointments without the support from health professionals. Identifying this gap in the market, a pilot study in Boston, successfully introduced non-clinically trained health coaches. The health coaches meet with the patients before and after clinical consultations, act as the patients' advocate and support the patients in their health journey. Since the focus is on prevention rather than treatment, the investment in health coaches is shown to pay off.

Correspondingly, we may identify current non-consumers in construction to anticipate how new-market disruption may manifest here. Although a lot of stakeholders are generally involved in construction projects, there are also rather significant groups of stakeholders that are typically not involved. This may for example include the expected users of a new bike path, the neighbours of a new subway station or the future cleaning personnel of a new school. New technologies such as virtual and augmented reality make it easier to involve users in the construction design at an early stage of the project. Likewise, new-market disruption may be expected to empower the users. Perhaps crowdfunding platforms can involve users in prioritizing new construction projects, or allow the future users to vote about design-related decisions during the project.

Today, many construction companies deliver a customized solution for each customer i.e. they deal with markets of one (Gilmore and Pine, 2000; Thuesen, Jensen and Gottlieb, 2009). In contrast, disruption theory presupposes a mass market where companies target customer segments with different offerings. This discrepancy between practice and theory challenges the relevance of speaking of new-market disruption in construction. Supposing that a market consists of one customer, identifying new-market disruption in construction would mean identifying just one new customer. Supposing, in contrast, that construction may be a mass market, new-market disruption entails developing standardised solutions for construction.

Focusing on Creating Customer Value

Describing how disruption will occur in U.S healthcare, Christensen *et al*., (2017) argue for changing the incentive structures from a fee-for-service to a value-based system. Healthcare practitioners could for example be reimbursed on account of the general health of their community opposed to on account of number of consultations. Furthermore, a value-based incentive system would entail an increased focus on prevention rather than treatment. Technological progress could support this focus on the preventive value of healthcare, as it enables continuous monitoring of peoples' health, behaviour and environment (Patou and Maier, 2017).

In construction, focusing on long-term value may mean measuring the indoor work environment and its effect on the users of the building, or utilizing measures of life-time environmental impact in the design of new structures. If companies in the construction industry start focusing on prevention rather than "treatment", facility management may likely play a bigger role in the design and construction phases. Furthermore, an increased focus on value would entail rethinking the contractual structures to align risk and reward and forming e.g. strategic collaborations.

In both healthcare and construction, it is difficult to change incentive structures and value networks. Especially because shifting to an incentive system that is based on long-term value typically will induce bad financial performance in the short run. Christensen *et al*., (2017) prescribe that legislators, providers and payers need to coordinate their actions in order to create sustaining changes. Although this is highly difficult, the benefits of disrupting the industry appear to be worth it.

DISCUSSION AND CONCLUDING REMARKS

Comparing healthcare and construction, a number of similar challenges and opportunities were identified. Both industries are characterised by a complex stakeholder network, misaligned incentive structures, improvement potential in the quality of offerings and limited investments in disruptive innovations. Assuming that the healthcare sector is indeed ripe for disruption, this comparison would suggest that construction is similarly ripe for disruption.

However, the identified similarities between healthcare and construction may also support another conclusion: that the construction industry, just like healthcare, is "impervious to even the strongest forces of disruption" (Christensen, Waldeck and Fogg, 2017, 4). Or perhaps more likely: disruption theory may not be the most appropriate theory for explaining the complex industrial dynamics of construction and healthcare.

This view is supported by Geels (2018) who has analysed the transformation of energy-related sectors to low-carbon energy systems. He argues that disruption theory's focus on single (conquering) innovations and price/performance competition makes the theory less suitable for studying system transitions, where e.g. social and political dimensions play a large role in creating change.

Correspondingly, we find that the strengths of disruption theory does not lie in its ability to predict when disruption will occur, but rather in its recommendations for envisaging how disruption could likely manifest. Taking point of departure in four recommendations from disruption theory, we have shown to which extent the lens of disruption may aid construction companies in anticipating changes.

As for the question of when disruption might occur, disruption theory falls short of an answer. Different industries have different trajectories of technological development, meaning, for example, that it took 40 years before mini mills had disrupted the steel industry (Christensen, Raynor and McDonald, 2015). Arguably, this may deflate the prescriptive value of speaking of ripeness for disruption. Although the industry is claimed to be ripe for disruption today, the lack of a specified timeframe makes it possible that the industry is still (or again) ripe for disruption in 15 years from now.

Not knowing when disruption will occur in construction (and assuming that it will), construction companies may benefit from following both market and technology development closely. Foresight methods may be helpful for imagining possible future, and technology management methods may aid the companies in identifying and assessing the potential of new technologies. As a part of our future research, we aim to combine the advantages of foresight and technology management and investigate new ways of assessing the disruptive potential of new technologies.

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Appendix B: The Horizon Scan Paper

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IDENTIFYING DISRUPTIVE TECHNOLOGIES: HORIZON SCANNING IN THE EARLY STAGES OF DESIGN

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Abstract
Technology development is accelerating, driving disruption. Design is seen as key differentiator in creating innovative offerings but few design methods consider future technologies explicitly. In this article, we explore how a foresight method, namely horizon scanning, may be applied in a design context to anticipate disruption of construction. By means of a 3-step horizon scan, we identify 133 potentially disruptive technologies from across industries. We find that when preparing for disruption, design may benefit from the future-oriented and technology-focused features of horizon scanning.

Keywords: disruption, horizon scanning, technology development, design methods, digital design

1. Introduction
Disruption has become an important point on the agenda in established companies. Stories like the ones of Blockbuster being disrupted by the adoption of video streaming, or Kodak being disrupted by the introduction of digital cameras linger in the boardrooms. Such stories warn established companies to stay up-to-date on new technology and create "disruptive" solutions to avoid being disrupted themselves. When companies seek to stay competitive, design is often seen as a key differentiator (Samperi et al., 2002; Stevens and Moultrie, 2011). It is well acknowledged that the ability to design new products and services that satisfy the changing needs of customers is essential for companies to become and remain successful. However, as technological development accelerates, it is increasingly important for companies to look beyond the development of the immediate next product or service (Samperi et al., 2002). In that regard, applying future-oriented methods shows great potential, as these methods allow companies to prepare themselves for the changes anticipated and possibly also to act earlier (Malhotra et al., 2015).
The benefits from focusing on future markets and acting early is also found in disruption theory. Bower and Christensen (1995) coined the notion of ‘disruptive technologies’ in 1995. Since then, the term disruption has become widely used academically as well as among business practitioners to describe technologies that are able to up-end markets by changing the bases of competition (Danneels, 2004). In order to avoid being disrupted, Christensen argued that incumbent companies should invest in disruptive technologies at an early stage and adopt the new technology before it matures (Christensen, 1997). Furthermore, Bower and Christensen warn well-managed established companies against ignoring new technologies, just because they are not (yet) able to fulfil the needs of the current customers (Bower and Christensen, 1995). Instead they argue that focusing on future needs, markets and customers is essential when dealing with disruptive technologies.

Drawing on these two points 1) the importance of investing in disruptive technologies while they are still immature and 2) the importance of predicting future needs, customers and markets, we argue that disruptive technologies are important to consider in the early phases of design. This is argued as the design process builds on technological opportunities as well as a thorough understanding of customers' needs - and the latter may well change when impacted by disruptive technology.

The potential benefits of applying future-oriented methods to design is not well described in design literature (Evans and Sommerville, 2007). Although designers may consider future as an intrinsic part of the design process, few design methods seem to focus on describing or imagining the future based on, for instance, trends and long-term technology development. Nevertheless, the fields of design and foresight have many similar characteristics, and in recent years the mutual benefits of translating methods and techniques for cross-fertilisation has gained attention from both fields (Rijkens-Klomp et al., 2017).

This article is guided by the following research question: How might horizon scanning be applied in the early stages of design to identify potentially disruptive technologies? We start by reviewing the notions of disruption and technology. Following this, the potential of using horizon scanning for early identification of disruptive technologies is outlined. To illustrate the potential, we present how horizon scanning was applied in the construction industry in the early stages of a design process; aiming at preparing the industry for disruptive changes. We end the article by reflecting on how design and foresight may cross-fertilise, and the usefulness of using horizon scanning for identifying disruptive technology is discussed.

2. Disruptive technology

2.1. Disruption

The theory of disruption provides an explanation to why well-managed companies fail in maintaining their market position when faced with new technology (Bower and Christensen, 1995; Christensen, 1997). The theory defines disruptive technology as opposed to sustaining technology and describes how disruptive technology "*bring[s] to market a very different value proposition than had been available previously*" (Christensen, 1997, p. xv). As Christensen has later emphasised, disruption should be understood as a process (Christensen et al., 2015). Typically, products based on disruptive technology enter a market offering low performance compared to the established counterparts in mainstream markets (Christensen, 1997). The disruptive technology tends to gain grounds among a new customer group – typically in the low-end of the current market – as the disruptive technologies generally are simpler and cheaper than established alternatives. As time passes, the disruptive technology develops and turns out to become competitive to the established products even in mainstream markets. In this way, established products are pushed off the market as the disruptive technology gradually gains more and more market shares.

The theory describes that disruption occurs because established companies tend to ignore disruptive technologies as long as the performance of these technologies is inferior to established products. However, arguing that technologies can develop faster than market demand, disruptive technologies that are underperforming today may actually satisfy the market tomorrow (Christensen, 1997). It is therefore important for incumbent firms to invest before the technology has matured enough to deliver a satisfactory performance in mainstream markets (Christensen, 1997).

Besides providing an explanation of why well-managed, established companies have lost significant market shares, the theory of disruption also provides guidelines for companies seeking to avoid being disrupted. According to the theory, incumbent companies should avoid evaluating the potential of disruptive technologies based on knowledge of current customer and markets. Instead the company should recognise that when dealing with disruptive technology, it is impossible to know the size of an emerging market, and instead apply a flexible discovery-based approach to evaluating market potential (Christensen, 1997). Moreover, the theory prescribes that the company should create an independent organisation and allocate resources to let this separate unit explore the potential of the disruptive technology.

Realising that the source of disruption is not always technology, but may also be for instance a business model, Christensen has replaced the term disruptive technology with disruptive innovation (Christensen and Raynor, 2003). Moreover, the theory has been refined to distinguish between low-end disruption (targeting customers in the low-end of the current market) and new-market disruption (targeting current non-consumers) (Christensen and Raynor, 2003). Although this has broadened the applicability of the theory, it also has diluted the understanding of what disruptive innovation may or may not be (Danneels, 2004; Markides, 2006).

In order to identify disruption early, Christensen and Raynor (2003) suggest a job-to-be-done approach, focusing on what kind of job the customers "hire" the product to do. This is coherent with a typical user-centred design process (as seen in e.g. Thorpe et al., 2016). However, the challenges following a user-centred approach are those of users trying to foresee their own needs and wants in the future. And other challenges include the difficulty of selecting an appropriate user group, knowing that disruptive technology may well cause the customer base to change. Therefore we propose that a design process preparing for disruption may benefit from combining a user-driven approach with a technology-driven approach.

In this article, we focus on disruptive technologies in contrast to e.g. disruptive business models or disruptive innovation. By limiting our focus to technologies in this article, we seek to anticipate disruption from the technology development perspective that originally was used to form the theory of disruption. But first, let us specify what we mean by technology.

2.2. Technology

Although the term technology is broadly used and understood, the definition of technology is not as clear-cut as one might think. It may be easy to recognise that a computer, a pen and a lawnmower are instances of technology. However, the term technology is also used to describe methods, skills and knowledge used to create technological artefacts, such as laser-printing, calculating or manufacturing. These two dimensions of technology can be named *technology as an artefact* (Kline, 1985; Digironimo, 2011) and *technology as a creation process* (Digironimo, 2011).

Zooming out and comparing technology to other broadly applicable terms, such as science or culture, a third dimension of technology is revealed. Digironimo (2011) calls this third dimension *technology as a human practice*. This dimension views technology as an integral part of being human, since technology has existed since before we became homo sapiens (Kline, 1985). Kline adds to this by describing technology as a sociotechnical system of manufacturing and use, and argues that it "*form[s] the physical bases of all human societies past and present*" (Kline, 1985, p. 217).

For the purpose of this article, we find it necessary to limit the perspective on technology. In the search for potential disruption, we are interested in concrete technologies that may radically change the parameters of competition in a given market. This may be technologies in the form of artefacts (such as autonomous cars) or creation processes (such as 3D printing). However, for the purpose of this study, we will not reflect on how technology affects our society, in the sense of technologies as human practice. Examples of technology as human practice may include notions such as automation and circular economy, which in this context will be considered as trends rather than technologies.

It is characteristic for technologies that they evolve over time (Cozzens et al., 2010). This evolution is often depicted as an S-curve showing how an emerging technology starts as unproved technological potential and gradually matures as the technology finds suitable application(s) and settles in the market. As acknowledged by Cozzens et al. (2010, p. 364), it is "*particularly important for a monitoring system to be able to detect emerging potentially disruptive technologies at the early stages of the cycle*". Searching for technologies that will impact future markets, we are interested in technologies that are currently in the early stages of the S-curve, i.e. as they emerge and develop and before they mature. Mature technologies such as pencils and laser-printing are therefore not considered relevant for this study. Building upon the above description of disruption and technologies, we have provided a theoretical foundation for understanding the nature of disruptive technologies. Reviewing the theory of disruptive technology, Danneels (2004) proposed a need for understanding how potentially disruptive technologies can be identified. In the following, we will address this need by presenting horizon scanning as a suitable method for identifying disruptive technologies.

2.3. The need for a future-oriented approach

Realising that in order to predict disruption, it is necessary to think about future technologies, needs and markets, it seems natural to look into the domain of technology foresight and forecasting in order to find a suitable identification method. However, the identification of disruptive technologies are not so easily caught by traditional forecasting methods (Cheng et al., 2017) or foresight (Dixon et al., 2014; Cheng et al., 2017). Most mainstream foresight and forecasting methods take their point of departure in the trajectories of technology development, and these methods are therefore much better at identifying the future development of sustaining technology than potentially disruptive. According to Georghiou and Harper (2013, p. 467) "*dealing with disruptive transformations is seen as the key forward challenge for the practice of FTA [Future-Oriented Technology Analysis].*"

Digitisation is often mentioned as a driver for disruptive changes (e.g. Wenzel et al., 2015; Stewart et al., 2017). Due to the lack of physical assets, digital solutions are less constrained by the typical boundaries of industries (Tilson et al., 2010). Taking this into account, it seems important for companies to be aware of technologies developing outside their own industrial domain. We therefore call for a broad method for identification of disruptive technologies across industries.

2.4. Horizon scanning

Corporate activities concerned with identifying new technologies is called technology intelligence. Kerr et al. (2006) have described four different technology intelligence modes that may be applied according to the needs and current knowledge of a company: mining, trawling, targeting and scanning. Although Kerr et al. (2006). argue that all four modes should be used concurrently, they also state that "*Organisations in sectors experiencing high rates of technology change or at greater risk to disruptive technologies will employ the scan mode to a greater extent than the target mode*". Moreover, if it is a managerial goal to understand what the company does not know that it doesn't know, a scanning mode is considered especially suitable. Considering that especially digital technologies create disruption across established industries, a cross-disciplinary and wide-ranging method such as horizon scanning is considered suitable.

Horizon scanning is a specific foresight method that is increasingly used by governments and private organisations to support decision making and policy development (Palomino et al., 2012).

Horizon scanning can be defined as "*the systematic search for incipient trends, opportunities and constraints that might affect the probability of achieving management goals and objectives.*" (Sutherland et al., 2011, p. 10). Horizon scanning is normally based on desk research and obtaining knowledge from e.g. industry reports, government reports, scientific publications, patents, news articles, conferences and surveys in order to anticipate issues and opportunities of the future. As has been emphasised by Sun and Schoelles (2013), the choice of sources for a horizon scan should depend on the mandate and goals of the specific horizon scanning program.

It may be useful to differentiate between two types of horizon scanning: issue-centred and exploratory (Amanatidou et al., 2012). Issue-centred scanning seeks to evaluate a specific hypothesis, which the scanning activity seeks to confirm or question by means of a focused search. This corresponds to the target-mode of technology intelligence as described by Kerr et al. (2006). In contrast, an exploratory scanning aims at identifying a long list of emerging issues, e.g. by examining at lot of topics from various sources and domains. Often both approaches are used interchangeably in different phases of the project, based on the objective of the scanning activity. Kerr et al. (2006) recommend a migration from the more exploratory scan mode to a target mode, where the benefits of specific technologies are investigated in detail.

As the future is unknown, it is hard to validate the results of a horizon scan before time has passed, revealing to what extent the predictions about future technological development turned out to be correct. Nevertheless, we argue that in order to prepare for disruptive changes, it is better for a company to have identified a broad range of technologies, of which some may show to be unimportant, than the opposite case of *not* having spotted a technology that turns out important. To illustrate the potential of using horizon scanning for anticipating disruption, we will now describe how we researched and used horizon scanning in the construction industry to identify new and potentially disruptive technologies.

3. Applying horizon scanning in the construction industry

3.1. The construction industry

To examine empirically how disruptive technologies may be anticipated by means of a horizon scan, we chose to take the point of departure in a specific industry, namely the Danish construction industry. This industry was chosen, as it faces a large number of multi-faceted challenges that may be tackled as design problems. Moreover, the industry is often described as conservative (Fuhr et al., 2009) also when it comes to adopting new technologies, and consequently the threat of disruption may no longer be hypothetical. Productivity of Danish construction has decreased with 0.5-1% per year in the period from 1995 to 2011, despite massive digitalisation and technological developments in these years. As comparison, the manufacturing industry increased its productivity with more than 2% per year in the same 16 year period, whereas the finance and insurance industry experienced an impressive productivity increase of 5.6% per year (DI's produktivitetspanel, 2013).

The low productivity of the construction industry is also a global challenge, which has led several analysts to conclude that the construction industry is now ripe for disruption (e.g. World Economic Forum, 2016; McKinsey Global Institute, 2017). Root causes include complex regulation, little cross-functional collaboration, lack of innovation, large dependency of public-sector demand, and a mismatch between risk and reward in contractual structures (World Economic Forum, 2016; McKinsey Global Institute, 2017). This results in building projects being poorly managed, taking longer than planned and surpassing their budget.

Global investments in construction technology has increased in recent years with 183% from 2014 to 2016 (Tracxn, 2017), suggesting that technologies will play an increasingly important role in the construction industry in the future. Considering how other industries, such as the automotive industry, have been radically transformed by the advent of disruptive technologies, there is arguably a good reason for construction companies to act proactively in this regard (World Economic Forum, 2016). From a construction company's point of view, there is a need for engaging in a design process aimed at utilising the opportunities of new technologies. We consider the future-oriented scope of horizon scanning to be especially helpful in this regard.

3.2. Horizon scanning in three steps

We conducted the horizon scanning activity in three steps, as illustrated in Table 1.

The first step, 'Defining', was to create a foundation for the horizon scan. First, we clarified purpose, target group, desired outcome and expected format. The purpose of the horizon scanning activity was to identify new technologies that would be relevant for an established company in the construction industry to consider when preparing the company for disruptive changes. In this regard, it was considered important to identify technologies broadly and across industrial domains without initial considerations regarding relevance to the construction industry. This meant that e.g. biomedical technologies (such as DNA writing) and space technologies (such as nanosatellites) were not considered any different from technologies developing within the construction industry (such as 3D printing concrete). This was done to keep an open-mind as to how the construction industry might benefit from any technological development, seeking to use this knowledge to create or predict disruptive opportunities.

More specifically, the desired outcome was described as a long list or a catalogue of emerging and potentially disruptive technologies. The primary target groups were managers and stakeholders from Danish construction companies interested in business development and/or preparing for disruption. The focus was on technologies in contrast to e.g. observed changes or potentially disruptive business models. Due to time constraints, a snapshot of emerging technologies was preferred as opposed to continuous or repeated horizon scanning. Considering the purpose of this horizon scanning, we decided to use an exploratory scanning approach looking for signals of emerging technologies across a wide range of sources.

Table 1. The horizon scanning was conducted in three steps

1. Defining	**Clarification of** • Purpose • Target group • Desired outcome • Expected format	**Identification of relevant sources** • Foresight reports • Business analyst reports • Industry-specific reports • Conferences
2. Identifying	**Scanning of literature** • Manual identification of technologies in reports • Marking which sources the technologies were found in	**Conference participation** • Manual identification of technologies being presented • Marking which conference a given technology was found
3. Synthesising	**Organisation of technologies** • Identifying synonymous technologies • Organising technologies based on frequency	

The foundation for the horizon scanning was laid out by collecting relevant reports. We identified relevant foresight reports to ensure that the horizon scanning was based on previous, thorough and broad horizon scanning activities conducted by e.g. governmental institutions. Moreover, we included reports from business analysts Gartner, IDC, and Forrester. These three business analysts have the largest influence on European customers as well as the most media coverage and financial attention among all industry analysts in the world (Ikeler, 2007; Dotsika and Watkins, 2017). Finally, we found industry reports that focused especially on the construction industry to ensure the identification of technologies from the targeted industry. All reports were based on comprehensive research and were independent of commercial interests. Considering that the target group was Danish, as well as the fact that technologies develop across country borders, we ensured that both Danish and international sources were represented. Furthermore, we identified 9 industry conferences and seminars targeted at participants from either construction, media, healthcare, R&D or technology-savvy people in general. The conferences/ seminars were included, if they had one or more presentations on currently developing technologies. In total, 11 reports and 9 conferences were included as sources, see Table 2.

Table 2. Sources for the horizon scanning

Count	Type of source	Description
2	Foresight reports	By public authorities - EU and Denmark
6	Technology reports	By Gartner, IDC, Forrester, McKinsey & Co., CB Insights
3	Industry-specific reports on the construction industry	By World Economic Forum, McKinsey & Co., Tracxn
3	Construction conferences/seminars	Themes: 3D printed construction, virtual design construction, annual construction seminar
1	R&D conference	Future Festival
1	Media conference	NextM
2	Healthcare seminars	Themes: disruption, blockchain
2	Technology conferences	Technomania, SingularityU Denmark

The second step 'Identifying' was to identify technologies. For that, we reviewed the 11 reports and identified emerging technologies described in the reports. This resulted in a long list of technologies. For each technology, we noted in which sources which the specific technology was mentioned. Furthermore, we participated in 9 industry conferences and seminars to obtain information from business and technology experts. Through presentations at the conference, we identified additional technologies and trends, which were added to the list. Again we noted at which conference we had heard about the technologies.

In the third step 'Synthesising', we went through the list of technologies. We found that some technologies could be defined as a subset of another technology on the list (e.g. machine learning and artificial intelligence), while other technologies were overlapping to some extent (e.g. Building Information Modelling and Virtual Design Construction). In some cases, we found that two terms were used interchangeably about the same basic technology (e.g. additive manufacturing and 3D printing, or wireless technology and 5G). In these cases, we considered both notions to describe one technology and combined them on the list. Next, we counted the number of times that a specific technology had been found across the 20 sources (11 reports and 9 conferences). We then organised the list based on frequency counts so that those technologies that had been found the most were placed at the top of the list.

3.3. Findings

All in all, we identified 133 technologies across industries. These can be seen in Table 3, where they are sorted based on the number of times each technology was found.

When evaluating technologies based on the number of times they occur, it is important to take into account that some of the listed technologies may be used as umbrella terms covering several other technologies on the list. This may result in umbrella terms being found more often than a specific sub-set technologies. Moreover, the current hype of certain technologies may also affect the number of times a specific technology is found. This may, for example, be the case for blockchain technology, which is a relatively new technology currently peaking on Gartner's Hype Curve (Furlonger et al., 2017). Nevertheless, we consider the number of times a technology has been found as a good proxy for understanding which technologies it will be hard to avoid when looking into the future.

3.4. Validation of findings

To deepen our understanding of technological impact in the future – and as a way of validating the results above – we conducted short interviews with 25 participants attending three conferences. These participants were all interested in technological development and represented a broad selection of different industries (e.g. digital marketing, transportation and hotel). We asked the participants which technology (or trend) they thought would have the biggest impact on the development of our society during the next 10 years. The results are seen in Table 4. (Some participants mentioned more than one technology, and the total sum of answers from 25 participants therefore sums to 27.)

Comparing the answers to the results of the horizon scan (Table 3), we see that all the technologies mentioned by the participants was also found in the horizon scan. This suggests that the most commonly found technologies from the horizon scan are also considered important by technology-savvy stakeholders across industries. Moreover, we find that 8 out of 10 technologies mentioned in the interviews are found 7 times or more in the horizon scan. We therefore suggest that the technologies at the top of Table 3 are especially important to be aware of when preparing for disruptive changes.

As can be seen from Table 3, the five technologies that were found the most were: Internet of things, artificial intelligence, big data analytics, robots and blockchain. This suggests that these technologies are especially important to integrate in a disruption-proactive design process.

Applying the identified technologies in a business development-oriented design process could entail questions like "Who might benefit from internet of things and the connected functionality it provides?", "How might artificial intelligence substitute one or more tasks in our industry?" or "What kind of data has value, we ought to utilize more, e.g. by means of analytics?". In this way the list may act as a possible solution list, for which the designer (in this case, business developers and policy makers in the construction industry) may not yet know the problem.

Although few of the technologies on the list are specific to the construction industry, it was possible to think of use cases in the construction industry for most of the technologies. We found that most of the reports and conferences that were specifically focusing on technologies used in construction did not pay much attention to the generic technologies emerging in other industries, such as blockchain or artificial intelligence. Presenting the results of the horizon scan to stakeholders in the construction industry, we found that it raised the awareness of the current technological development happening across industries, and ignited conversations about possible future development. The horizon scan facilitated questions like "How might we use the blockchain technology in our industry?" instead of focusing only on technologies that have already proven useful in construction. In this way, the horizon scan facilitated an open-minded conversation about how construction may be disrupted by new technology.

Table 3. The identified 133 technologies organised based on the number of times the technologies were found in 20 sources

Count	Technologies		
14	Internet of things		
13	Artificial intelligence		
12	Big data analytics / business analytics		
11	Robots		
10	Blockchain		
9	Virtual reality	Additive manufacturing / 3D printing	
8	Autonomous vehicles	Deep learning algorithm	Machine learning
7	Augmented reality	Voice control / Natural language processing / conversational user interface	
	Cloud computing	Mobile connectivity / Wireless / 5G	Drones / UAVs
6	Virtual personal assistants / smart advisor / chat bot / cognitive expert advisor		Synthetic biology
	Quantum computing		
5	Smart city	Building Information Modelling (BIM)	Connected transport / Smart transport
	Bioinformatics		
4	Battery technology, e.g. lithium-ion	Generative Design	Cognitive computing
	Wind and solar power	Bitcoins	Carbon nanotubes / graphene
	Health monitoring wearables or implants / Personal health screening		Genome editing, e.g. CRISPR
	Human augmentation/Augmented sensing		
	Brain-computer interface / Implantable direct neural interface		
3	Biofuels	Computer vision / machine vision	Predictive diagnosis based on genes
	Carbon capture and storage	Emotion recognition	DNA writing
	Virtual customer assistants	3D printing construction	DNA sequencing
	Personal identity and data mngt.	Self-cleaning surfaces	Personalised medicine
	Serverless services (PaaS, IaaS, SaaS)	Functional materials	Biochips and biosensors
	Edge computing	Self-healing materials eg. concrete	Project lifecycle management
	Photonic computing	Exo-skeletons / Augmented mobility	Construction robots
	Prefabricated volumetric construction / Modular construction		Machine-to-machine-communication
	Tissue engineering / Augmented biostructure		Neuroprosthetics
	Neuromorphic hardware / Neurosynaptic chip		Modelling simulation and gaming
2	Real-time weather data	Machines in charge of own money	Genetic engineering
	3D scanning	Parallel or grid computation	Regenerative medicine
	Cellular agriculture / synthetic food	DNA computing	Biocatalysis
	Electric vehicles	Mixed reality	Smart infrastructure
	Fuel cells	Volumetric display	Hyperloop
	Fossil fuel exploration and recovery	Smart dust	Virtual Design Construction
	Nuclear fusion	Digital twin	Flying cars
	Augmented data discovery	Wearable or implantable translators	Construction marketplace /e-auction
	IoT analytics incl. location analytics	Humanoide robots	Micro and Nano satellites
	Augmented analytics	Nano-bots / Nanodevices in healthcare	Space transport
	Micropayment	Self-assembling/organizing structure	Colonization of space
	Nanomaterials	Precision agriculture / precision farming / site-specific crop management	
	Smart contracts		
1	Accurate GPS data	Autorouting	Real-time diagnostics support
	Smart countryside	Data mining	Medical and bio imaging
	Power microgeneration	Enterprise taxonomy /ontology mngt.	Stem cells
	Off-the-grid / autonomous building	Software-Defined Security (SDS)	Smart building
	Smart grid	Citizen science	Data driven facility management
	Advanced water purification	RFID tags	Smart workplace
	Digital agriculture (GMO 3.0)	Surface computing	Accident prediction and prevention
	Coating food to extend shelf life	Biometric identification	Smart robots
	Marine and tidal power	Metamaterials	Biomimetrics / nature-inspired design
	Harvesting energy from space	Piezoelectric materials	Circular construction
	Energy from human motion	Collaborative robots	Geo-engineering
	Hydrogen Energy	Autonomous delivery robots	Robotic process automation
	Automated bulldozers and autonomous haul trucks		Nuclear fission

Table 4. The technologies that 25 interviewed participants thought would have the biggest impact on our society in the next 10 years

No. of answers	Technologies		No. of answers	Technologies
6	Artificial intelligence		2	Blockchain
6	Virtual reality		1	Augmented humans
4	Internet of things		1	Autonomous cars
3	Augmented reality		1	Nanotechnology
2	Big data		1	Voice controlled interfaces

Many of these technologies are to a large extent digital. Recalling that digitisation is a driver for disruptive change, we suggest that the degree to which a technology is digital is an important factor to be aware of when seeking to anticipate disruption. This relation would be interesting to examine in further work. Further work might also include exploring the potential of specific technologies from the list and discovering suitable application areas. This corresponds to a migration from the scan mode to the target mode, which is recommended by Kerr et al. (2006). The potential of a specific technology might be explored through an innovative design process, which is able to translate between different industrial domains and take the user perspective into account. Exploring different application areas for the same technology may benefit the design process as well as inform and qualify the foresight process.

4. Discussion

In the following, we will start by discussing the applicability of the horizon scanning method. Next, we will discuss implications of applying the method for identifying disruptive technologies in construction, to what extent this may transfer to other industries, and how design may benefit from it.

As shown above, horizon scanning used for exploratory purposes enables the identification of a large number of technologies while they are still in the early phases of development. This allows companies to gain the kind of first-mover advantage that according to Christensen (1997) is necessary when dealing with disruptive technologies. Nevertheless, the horizon scanning method also has some limitations. The method has been criticised for its superficial "scattergun approach" that does not reveal the implications of (or linkages between) different technologies (Georghiou and Harper, 2013, p. 468). Furthermore, it is arguably difficult for a company to take investment decisions based on the long list of emerging technologies without guidance towards the level of disruptive potential of the listed technologies. Not knowing the exact potential of the listed technologies may though also be seen as a strength of using horizon scanning in preparing for disruption. This is argued as the potential of disruptive technologies is inherently difficult to predict compared to the potential of sustainable technologies (Christensen, 1997). Nevertheless, supplementing the exploratory scan with an issue-centred scan may be necessary industrial context to provide a sufficient foundation for decision making.

One might argue that identifying disruptive technologies is only one small step in preparing a company or an industry for disruption. We agree. Not every technology on the list represents an opportunity or threat to the target company/industry, and there is considerable work in selecting the best technological opportunity and developing it so it fits with the context, generates profit and satisfies customers. It is also necessary to take a lot of industry-specific factors into account, e.g. current processes, stakeholders, roles, regulations, or business model opportunities. However, developing an industry or company to prepare for disruption, it is important not to let the immediate challenges be a barrier for development. Instead of defining customers, competitors, offerings and industry boundaries in advance, horizon scanning encourages the target group to think about the future, see new links and translate ideas from one industrial domain to another. This also means that the result of the horizon scan is generic. We have shown how the method was applied in the construction industry; nevertheless, only few technologies on the list are construction-specific. This suggests that the results may also be valuable in other industries beyond construction.

Looking through the list of technologies, we found that the technologies on the rise in construction (e.g. Building Information Modelling or 3D printing construction) were typically not mentioned in the generic sources focusing on emerging technologies. We therefore found it valuable that we had explicitly searched for sources focusing on construction technologies as a part of step 1 in the horizon scan. Transferring this horizon scanning method to another industry, we suggest it may be useful to include sources that focus specifically on technological development of the industry sector in question. Preparing for disruption is not a clear-cut task. Nevertheless, disruption theory as well as other theories (e.g. Ismail et al., 2014) agree on the importance of experimenting with the emerging technologies in order to identify their potential. From a business administration point of view, Christensen (1997) advises companies to apply a discovery-driven approach where (potentially) disruptive technology should be introduced in the market in a small-scale and easy modifiable version. From a design perspective, this corresponds to an iterative and experimental design process that is adaptive to stakeholder responses.

Design processes are typically seen as a co-evolution of problem and solution (Dorst and Cross, 2001). We argue that horizon scanning can aid the exploration the solution-space, as the listed technologies represent different possible or impossible solutions to a design problem. However, one might also argue, that the technologies represent various problems of the future that needs to be tackled through design. Although we cannot be fully be sure that the identified technologies will turn out to create disruption, we argue, that identification in itself will benefit the design process, as it allows for an open-minded approach to what might be. The horizon scanning method differs from other design methods that systematically explore possible solutions to a design problem (e.g. QFD, morphological charts), because it takes point of departure in a design problem that is not (yet) known. We therefore see horizon scanning as a good supplement to a problem-exploring approach, where e.g. stakeholders are involved in explaining what is and imagining what could be. By creating awareness of future scenarios and potential solutions, the horizon scanning method may aid the designer in anticipating future design problems and in working towards sustainable futures. And keeping in mind that technologies can develop faster than market demand, we argue that the ability to foresee future challenges is an essential part of preparing for disruption.

5. Concluding remarks

Preparing for disruption is on the top of the agenda in many industries. This affects the design of new products and services, as companies strive to stay on top of technological advancements. In this article, we have shown how the foresight method horizon scanning may be used to identify new technologies with disruptive potential. We have reviewed the notions of disruption and technology, presented the horizon scan method, and shown how applying the method in the construction industry led to the identification of 133 technologies. The identified technologies is developing in different industries such as healthcare, space and IT. The cross-industrial approach ensures that traditional industry boundaries does not limit the design of disruptive ideas, which arguably is important when preparing for disruption. This article contributes to both practice and research. For practice, we have described a three-step process for conducting a horizon scan, and hereby identified 133 potentially disruptive technologies. For research, we have argued for the relevance of applying of horizon scanning in design and demonstrated how horizon scanning may be applied in the early stages of design in order to anticipate disruptive technologies.

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Appendix C: The Vision Paper

Ernstsen, S. K., Whyte, J., Thuesen, C., and Maier, A. (2021). “How Innovation Champions Frame the Future: Three Visions for Digital Transformation of Construction.” *Journal of Construction Engineering and Management*, 147(2016)

How Innovation Champions Frame the Future: Three Visions for Digital Transformation of Construction

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Abstract: Digital technologies are expected to create transformational change in the construction sector. Previous studies have either anticipated the impact of individual technologies or outlined a number of nontechnology-focused future scenarios. There is comparatively little work on how innovation champions frame the future by combining a range of digital technologies and trends (such as big data, the internet of things, and automation) to transform construction. Drawing on an interview-based study with UK construction professionals, this paper presents three emergent visions for digital transformation of the sector. These visions are efficient construction, user-data-driven built environment, and value-driven computational design. Arising in practitioner narratives, these visions all emphasize different technologies and are partially influenced, intertwined, and interconnected with technology, business, and policy discourses in the sector. Furthermore, the visions represent different trajectories for implementing digital technologies in the construction sector. This paper contributes to work on construction foresight and innovation discourses by articulating the multiplicity of visions for digital transformation of construction. This has implications for researchers, practitioners, and policy makers responsible for the digital transformation of construction toward possible, profitable, and desirable futures. **DOI: 10.1061/(ASCE)CO.1943-7862.0001928.**

Introduction

In a time of rapid change, construction companies need to innovate to remain competitive (Tatum 1989). Much construction research has studied the nature of innovation in construction (e.g., Gann 2003; Harty 2005; Ozorhon and Oral 2017; Slaughter 1998) and has regarded innovation as an important component in improving the performance of the construction sector (Gambatese and Hallowell 2011; Xue et al. 2014). According to Winch (1998), one of the most consistent findings in such research is that innovation requires champions. Innovation champions are described in the literature as individuals who are capable of promoting innovation despite opposition and who inspire others with regard to their vision for the future (Leiringer and Cardellino 2008). Moreover, these champions are willing to take risks and are capable of telling convincing narratives to gain the commitment of others (Sergeeva 2016).

In their study of examples of successful construction innovation, Nam and Tatum (1997) highlighted the importance of technically competent innovation champions. As technology has the power to transform existing construction-related products, services, and work processes, much construction research has studied the impact, adoption, and implementation of specific digital technologies in construction. For example, Dossick and Neff (2010) studied the implementation of building information modeling (BIM), Teizer et al. (2012) examined the potential of and barriers to nanotechnology, Whyte and Nikoli´c (2018) explored the practical use of virtual reality (VR), Li et al. (2019) investigated the role of blockchain, and Sawhney et al. (2020) recently proposed a framework for Construction 4.0. Several studies have anticipated that individual digital technologies will be able to change the competitive landscape for construction companies. Fewer studies have explored how innovation champions expect a combination of multiple digital technologies to affect the construction sector (a notable exception is Erdogan et al. 2010). Furthermore, construction practitioners remain unsure of what digital technologies to implement and how to implement change (Lavikka et al. 2018).

Nam and Tatum (1992) argue that construction companies can improve their innovation capability by taking leadership and applying a technology-push strategy with long-term perspectives, with later construction researchers articulating the benefits of long-term planning and foresight studies (Chan and Cooper 2011; Dixon et al. 2018). However, as a result of the unpredictability of the construction market, inadequate resources, and unstable employment, the capacity for long-term planning is low in construction practices (Soetanto et al. 2007). Questions arise about how futures are brought into being.

Innovation champions arguably play an important role, as they use narratives of the future to promote innovation and shape technological futures. To ensure internal and external credibility, innovation champions may align their narratives or visions with wider sectoral discourses (Leiringer and Cardellino 2008). Studying policy discourses of the UK construction sector, Smiley (2016) has argued for the need to explore multiple alternative futures:

> “contemporary construction policy discourses are in danger of becoming increasingly myopic, with alternative perspectives and visions increasingly marginalised, and so any potential for the flexible adaptation or reimagining of future policies is reduced.” (Smiley 2016, p. 4)

Sergeeva and Green (2019) have built on this argument and identified a need for understanding how construction practitioners interpret innovation and for comparing this to current policy discourses. In addition, they have emphasized the relevance of understanding construction innovation through the narratives of innovation champions.

This work contributes to the development of such an understanding. It explores construction practitioners’ expectations for the future of digital transformation in the sector through interviews with 13 innovation champions from the UK. The work builds on the aforementioned previous studies that anticipate the impact of individual technologies or outline a number of nontechnology-focused future scenarios. It extends this work to focus on how innovation champions frame the future by combining a range of digital technologies and trends [such as big data, the internet of things (IoT), and automation] to transform construction. It situates the three visions that emerge in the narratives of innovation champions within wider technology, business, and policy discourses. The next section describes the theoretical background to the paper in the work on construction futures, and the following section then describes the research method used in the study. The subsequent section describes the three identified visions for digital transformation of construction, and the following section compares and contrasts the three visions. The next two sections describe a set of innovation discourses that span technology, business, and policy and discuss how the visions are situated within these. The article concludes by summarizing contributions to practice and future studies research by presenting three distinct visions for digital transformation of the construction sector. These visions may serve as a narrative reference point for debates and aid the development of research, long-term company strategies, and sectoral policy, thereby constructing futures that are possible, profitable, and desirable.

Theoretical Background: Construction Futures

Narratives may be used to shape the future. In this regard, scenario planning and visioning are two well-known foresight methods for communicating possible or preferred narratives of the future (e.g., Doericht 2013). Narratives in the form of scenarios or visions can motivate stakeholders to think about how they may respond to a range of potential future changes, thereby improving strategic decision-making (Dixon et al. 2018; Harty et al. 2007). Moreover, both visions and scenarios encourage construction stakeholders to disregard traditional organizational boundaries and consider a range of trends and technologies in their exploration of the future.

Scenario planning is a structured foresight method that typically builds on the identification of social, technological, environmental, economic, and political (STEEP) trends. Several researchers have facilitated the development of future scenarios for construction (Erdogan et al. 2010; Harty et al. 2007; Lavikka et al. 2018). For example, Lavikka et al. (2018) and Erdogan et al. (2010) have described well-executed scenario planning processes in the construction sector, resulting in four exploratory scenarios for the future. However, in both cases, the resulting four scenarios focus on key trends and downplay the impact of digital technologies in favor of other aspects such as interorganizational structures and business models. To address this issue, Erdogan et al. (2010) supplemented the four scenarios with a comprehensive vision for construction information technology (IT) in 2030. This vision was created from the perspective of IT experts, and Erdogan et al. (2010) proposed that further research could benefit from considering the perspectives of other construction professionals.

Visions, similarly to scenarios, are exploratory in nature; however, they are different from scenarios because they are inherently positive and desirable descriptions of the future (Levin 2000). This is beneficial as “the future can be influenced if we know what we want it to be” (Erdogan et al. 2010). Being narratives by nature, visions utilize the power of storytelling, which triggers the imagination required for devoted actions from stakeholders (Levin 2000). While narratives are considered accounts of the future formulated at an individual level, they are often rooted in discourses that are shared among different individuals, organizations, and institutions. Narrative visions are thus a way for innovation champions to promote innovation in the construction sector. This paper correspondingly presents findings from interviews with innovation champions by means of narrative visions for the future of construction.

Research Method

The method applied in the research is based on the five phases illustrated in Fig. 1. Phases 1–4 cover the main empirical research on how innovation champions envision the future of construction through (1) selecting innovation champions, (2) interviewing innovations champions, (3) identifying future aspects, and (4) synthesizing visions. Subsequently, it became clear that the visions should be understood in a broader sectoral context and, thus, the fifth phase on mapping innovation discourses was added.

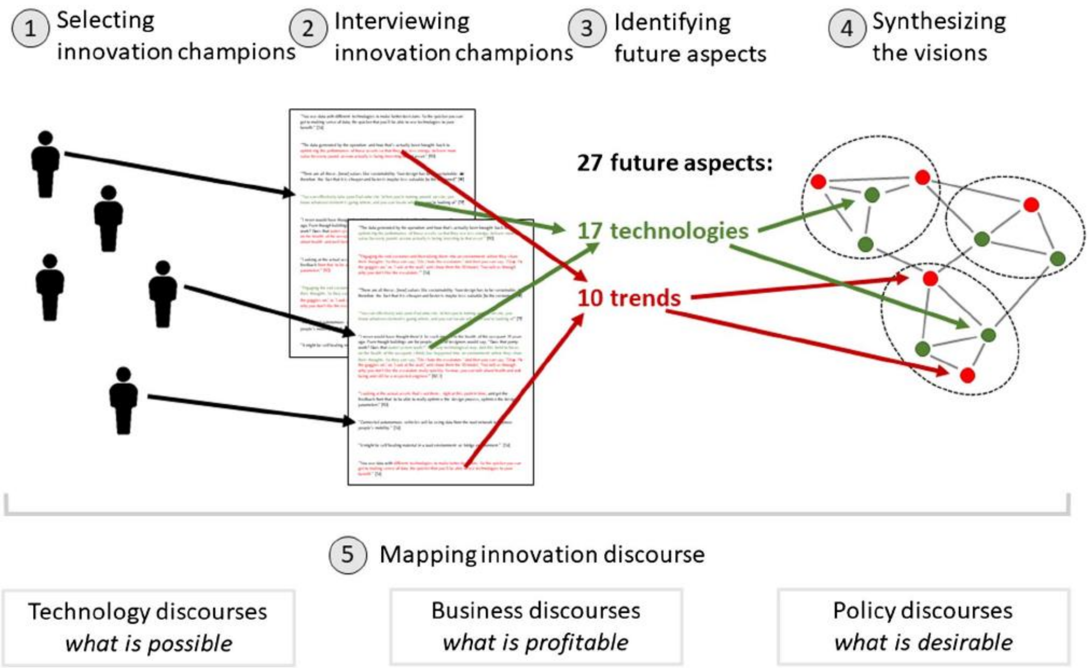

Fig. 1. Five phases of the research method. [Person icon by Universal Icons, under CC Attribution 3.0 (https://creativecommons.org/licenses/by/3.0/us/legalcode).]

Selecting Innovation Champions (Sampling Approach)

In sampling a relevant set of innovation champions, the study drew on Leiringer and Cardellino's (2008) conceptualization of innovation champions. The interviewees' formal titles were, for example, *group innovation and knowledge manager* and *business development director*. The authors consider the interviewees to be innovation champions through the role they had in the companies they represented and by their peer recognition as thought leaders, framing industry understandings of digital futures. The size of the sample was defined by the initial identification of relevant interviewees by the researchers and by a snowballing strategy in which the initial selection of innovation champions identified innovation practitioners they considered their peers. Most of the interviewees were in charge of innovation, digitalization, technology development, or business development within their company, and the remaining interviewees had a similar role as change agents within the sector. The final sample included 13 UK construction professionals from 10 companies.

The interviewees represent 10 small and large companies in the UK construction sector. The companies operate in the infrastructure industry, the building industry, or both. Four companies are engineering consultancies, three are contractors and three are small enterprises. An overview of the companies is found in Table 1.

Table 1. Company sample.

Company	Company size	Company type	Sub-sector
A	large	Contractor	Infrastructure
B	large	Engineering consultancy	Infrastructure
C	small	Management consultancy	Infrastructure
D	large	Engineering consultancy	Building and infrastructure
E	small	Technology start-up	Infrastructure
F	large	Contractor	Building and infrastructure
G	medium/large	Engineering consultancy	Building
H	large	Engineering consultancy	Building and infrastructure
I	medium	Contractor	Infrastructure
J	small	Innovation agency	Building and infrastructure

Interviewing Innovation Champions (Data Collection)

The interviews were semi-structured (Kvale and Brinkmann 2009) and were conducted in September and October 2018. Each interview lasted approximately 1 h and was recorded and later transcribed. The purpose of the interviews was to elicit how innovation champions envision the future of construction. However, as this is a rather difficult question, the interview guide was carefully developed to build up trust between the interviewer and interviewee (and get the interviewee talking) before discussing the difficult questions of what the future will look like. Correspondingly, the interviews started out with questions relating to how the company dealt with digitalization before the interviewer asked the interviewees about their personal opinions of digitalization and expectations for the future. The specific questions were intentionally open-ended to encourage the respondents to give long, narrative answers. This included several *how* questions intended to capture the interviewees' personal perspective of construction futures and the role of digital technologies. The central question that this paper primarily draws upon was the following: How do you envision the future of construction (e.g., how will we design and construct buildings 15 years in the future)? The interviewer encouraged the interviewees to be specific and give concrete examples of the impact of technologies, including descriptions of work processes and stakeholder relations.

Table 2 shows an overview of the interviewees. Each interview has been assigned a unique identifier showing which company the interviewee represented. All interviews involved only one interviewee and one interviewer, except for Interview 8, which involved three interviewees from the same company. All interviews took place face-to-face, typically at the interviewee's workplace; the exception was Interview 11, which was conducted via Skype version 2019.

Table 2. Interviewee sample.

Interviewee	Job title	Department / area	Length (hh:mm)
1A	Manager	Innovation and knowledge	01:38
2A	Manager	Sustainability	00:55
3B	Senior Engineer	Digitalization / BIM strategy	00:55
4C	Independent consultant	Major projects	00:49
5D	Project Director	Major projects	01:22
6E	Co-founder and CEO	Technology development	01:02
7F	Engineer	Engineering excellence	00:55
8G1	Head of Department	Sustainability	
8G2	Associate Director	Performance	00:56
8G3	Consultant	Performance	
9H	Associate	Foresight	01:01
10I	Director	Business development	00:55
11J	Independent consultant	Digital transformation	01:07

Identifying Future Aspects (Qualitative Coding)

All audio recordings were transcribed, summing to a total of 104,200 words. The authors read the transcripts and gained an impression that several interviewees shared similar visions for the future. The authors therefore imported the interview transcriptions into qualitative data analysis software (ATLAS.ti version 8.4.14) to allow for iterative coding of the content.

The analysis software was used to highlight parts of each interview in which the interviewees described an aspect of their envisioned future. The qualitative coding process was conducted iteratively to identify patterns across the interviews. Initially, the focus was on understanding what technologies the interviewees would find important and how the technologies would shape the future of the construction industry. Therefore, codes were assigned to the quotes that mentioned particular technologies. However, these technologies were not sufficient to describe the interviewees' visions of the future. The interviewees also described trends that they believed would affect the future, such as sustainability or standardization. To capture this dimension, 10 further codes were added. The 17 technologies and 10 trends represent 27 future aspects, see Table 3.

Table 3. Overview of future aspects (technologies and trends).

Identified technologies	Identified trends
Building information modelling (BIM)	Lean processes
Artificial intelligence (AI)	Alliancing business models
Design automation	Standardization
Big data	Safety on-site
Internet of Things (IoT) asset management	No disruption
IoT energy consumption	Sustainability
Augmented reality (AR) on-site and maintenance	End-user focus
	Bespoke semi-automation
Virtual reality (VR) and immersive design	Data-driven companies
Future materials	Gig economy
Connected autonomous vehicles (CAVs) and tunnels	
Digital fabrication on-site	
Design simulations	
Blockchain	
Digital twin of city	
Distributed off-site production	
Modularization	
Off-site construction	

Note: AR = augmented reality; AI = artificial intelligence; BIM = building information modeling; CAV = connected autonomous vehicles; IoT = internet of things; and VR = virtual reality.

Synthesizing the Visions (Data Analysis)

To some extent, the interviewees shared a common vision for the future. Reading through the transcriptions, the authors gained the impression that the interviewees committed to one of three distinct visions for the future. To explore this further, the authors recognized a need for concretizing each narrative. Narratives of the future are by nature not very tangible - and describing to which extent different narratives overlap can therefore be difficult. To cope with this, the paper conceptualizes a narrative vision as a combination of several different future aspects.

Each interviewee mentioned several different future aspects when he or she described a narrative vision for the future. This paper considers two future aspects as connected if they were mentioned by the same interviewee. Consequently, the combination of future aspects can be visualized by means of network analysis.

The network analysis software Gephi version 0.9.2 was used for building a network graph (Fig. 2). The authors exported a data table from the analysis software (ATLAS.ti). This table, which connected each interviewee to a number of future aspects, was then imported into the network analysis software (Gephi). In total, 158 empirical statements were imported, connecting the 27 future aspects through 234 edges (links).

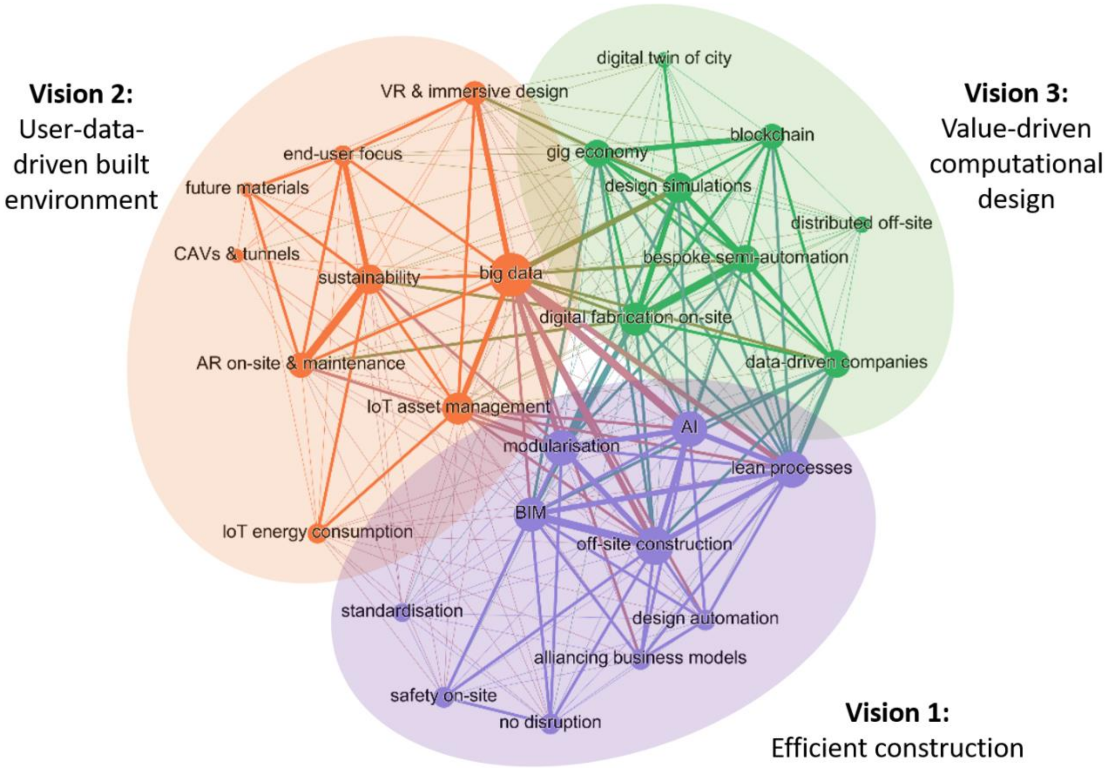

Fig. 2. Future aspects elicited through interviews are clustered to form three visions for the future: efficient construction, user-data-driven built environment, value-driven computational design. AR = augmented reality; AI = artificial intelligence; BIM = building information modeling; IoT = internet of things; VR = virtual reality; and CAV = connected autonomous vehicles.

Two nodes (i.e., future aspects) are connected if they are both mentioned by the same interviewee. In this way, the edges represent a direct account of the interviewees' understanding of how future aspects are connected. The following quote exemplifies how an interviewee connects the two future aspects big data and IoT asset management.

> "How can we think about connecting, for example, the traffic data to an office use, to public transport use, to weather data? It could be bringing a lot of these different functions of everything around us to optimize and deliver a better performance from the assets. Digital infrastructure is… to get more of those IoT sort of stuff into our infrastructure." [Interviewee 5D - engineering consultancy]

Other interviewees also mentioned these two future aspects, suggesting that big data and IoT asset management (for example) are heavily connected aspects of the future. In other words, these two future aspects are often combined into one narrative of the future— and one might assume some degree of dependency between the two. To visualize to which extent future aspects are connected, the thickness of the connections represent how many unique interviewees have mentioned both of the connecting future aspects.

In some interviews, an interviewee would describe a certain aspect of the future [e.g., artificial intelligence (AI)] in great detail and then briefly mention another future aspect (e.g., off-site construction). To account for this, the size of the nodes represents the number of times this specific future aspect was mentioned by any interviewee (counting also the number of times it was mentioned by the same interviewee).

The authors applied a ForceAtlas algorithm in Gephi to ensure that heavily connected nodes were placed in the middle of the network. This helped identify future aspects that were often mentioned in the interviews, that is, highly likely aspects of the future (according to the interviewees). Correspondingly, the future aspects located far from each other in the periphery of the network do not necessarily align or support the same narrative vision for the future.

To explore how the future aspects combined to form different visions for the future, the authors used Gephi to identify clusters in the network. By means of the Louvain method (Blondel et al. 2008), the software analyzed the network density and identified three clusters, which were characterized by a high degree of internal compared to external connections. The authors analyzed the clusters and used the insights from the interviews to describe three distinct visions for the future of construction.

Mapping Innovation Discourses (Contextualizing the Findings)

During the empirical study, the authors also sought to compare and contrast emerging findings with research literature and industry reports on sectoral discourses that might influence the narratives of construction futures. Thus, secondary data was collated to understand the context of innovation discourses, and after establishing the visions, it was clarified how they relate and should be understood in a broader sectoral context. As this understanding of the visions developed, three wider discourses became seen as interesting: (1) technology discourses driven by researchers and innovators considering what is possible, (2) business discourses created and promoted by management consultancies considering what is profitable, and (3) policy discourses developed by governmental bodies considering what is desirable.

Three Visions for Digital Transformation of Construction

The interview data suggests that innovation champions frame digital transformation through multiple competing visions of the future. Through the synthesis, three visions for digital transformation in construction were identified. Fig. 2 illustrates how the 27 identified future aspects form three clusters representing the visions: (1) *efficient construction*, (2) *user-data-driven built environment*, and (3) *value-driven computational design.*

In the following subsections, the three visions are described and supported by quotes from the interviewees. To enable validation of the network analysis, Tables 4–6 document the future aspects comprising each vision by means of exemplary statements. Furthermore, the tables list the number of interviewees mentioning each future aspect. The tables are organized according to network centrality, so the most central future aspect is listed first.

Vision 1: Efficient Construction

The cluster in the lower part of Fig. 2 forms one vision for the future. Interviewees who outlined this future emphasized the need for making the construction process faster and more efficient. Due to the focus on efficiency, this future vision is labeled *efficient construction*. The vision is centered on aspects such as off-site construction, AI, modularization, BIM, lean processes, standardization, no disruption, safety on-site, alliancing business models, and design automation (Table 4).

In this future vision, BIM is central and fully implemented in all phases of construction projects, as it is vital that all information be fully digital. BIM is used to enable smooth transactions and information flow between the various parties in the supply chain:

> "BIM is really important. It's the interface between each of the parties and each of the phases of the life cycle, and making those as smooth as possible so that you can locate the information, you know what to do with the information when you have it, you know what permission you have for it, and then you can reuse it without having to retype it into a computer so we're not passing PDFs or unreadable information around we've got. That's going to be the real key." [Interviewee 3B - engineering consultancy]

Thus, efficient construction is seen as BIM-enabled, with all parties interfacing through the use of the same reusable information. Inspired by the principles of lean manufacturing processes, the majority of building components are now standardized by reducing complexity and removing unnecessary variability in construction designs:

> "Why do we have so many different types of pile holes we dump into the ground? So many different diameters... Can we find ways to standardize that? … We're going to have five different types, and they will be these diameters. Some areas might be slightly over-designed, but some areas will be optimized. And overall you get a better optimization in terms of costs and quantities." [Interviewee 5D - engineering consultancy]

Standardization increases efficiency through leveraging learning effects and economy of scale. It is furthermore supported by modularization of construction elements and off-site prefabrication, allowing for faster on-site assembly. This has implications for construction workers' tasks, which have changed as the need for manual handling of construction materials decreased. Consequently, safety for on-site workers is improved, and fewer people are now working on construction sites:

> "Most of the buildings these days can be modularized… The details can be developed such that there is no huge need for people on the construction site to interact with construction materials… You will effectively build every section using technology that is already developed and used in manufacturing lines." [Interviewee 7F - contractor]

This vision includes no big bang type of disruption in the sense of new entrants managing to gain large market shares. On the contrary, the established construction companies have managed to make a slow and steady transition to a digital and lean way of working. The various parties in the supply chains now interact and collaborate digitally by means of strategic collaboration contracts:

> "I think generally, the contracts are moving much more into alliancing models and we're thinking more about integrators and delivery partners, rather than designer and constructor… So what we'll see is shared liability and shared risk and opportunity across project deliveries or program delivery" [Interviewee 3B - engineering consultancy]

These longer-term alliancing business models and strategic collaborations allow construction companies to optimize solutions and processes, not just in single projects but also at the portfolio and program level. They create a fruitful context for organizational learning by which the efficiency of construction is improved.

Long-term business models further enable investment in automation of design tasks, thus eliminating the most repetitive work and making the design process more efficient:

> "[If] we know that there's not [just] one single water supply project or drainage project, there's going to be 25 of them over the next three, four years… we could actually invest time into getting that standardized design automated. And then the contractor can standardize their manufacturing or installation process. So you start getting efficiency out of that." [Interviewee 5D - engineering consultancy]

As certain design tasks are automated, construction designers begin utilizing AI technologies, such as generative design and parametric design, to vary the input parameters and consider hundreds of design alternatives from an early stage in the project:

> "Generally [today], when you have a new project coming in, let's say a stadium, we say, 'Let's do a steel stadium'. That decision is a massive decision. It has a huge implication on cost. It has a huge implication on looks, … on carbon, etc. But it's made like that. Right? But could we actually explore … 'What if I do the stadium in timber or in concrete?' That is very exciting." [Interviewee 9H - engineering consultancy]

In this vision, AI not only expands the solution space for construction design, it also increases the efficiency of construction planning processes by exploring and evaluating a number of alternative construction schedules.

Table 4. List of future aspects forming Vision 1: efficient construction

Future aspect	Centrality	Mentioned by	Quote example
Off-site construction	0.93	[3B] [5D] [7F] [10I] [11J]	"You will see lots of prefabricated long section corridors of MEPs, ductworks, and cabling, and stuff already prefabricated in the factory and delivered on-site" [7F]
Artificial intelligence (AI)	0.91	[3B] [5D] [9H] [11J]	"[AI] will make it very much faster to make the initial estimates of how a design will affect the cost and the size, the time it takes to build the building" [9H]
Modularization	0.91	[5D] [7F] [9F] [11J]	"[A building] can be modularized as a volume or it can be modularized in component parts." [7F]

Building Information Modelling (BIM)	0.89	[3B] [4C] [5D] [7F] [10I]	"The BIM thing is all about handing over digital information to the contractor so that they can do their piece, and that the contractor hands over digital information to the maintainer and the operator so they can do their piece." [3B]
Lean processes	0.86	[3B] [4C] [5D] [11J]	"I think the role of technologies are to simplify the interface between the different parties and to ... limit the barriers between organizations … in kind of the larger sense, how does design speak to construction, speak to maintenance?" [3B]
Standardization	0.67	[5D] [8G1]	"The type of beam we might use in a housing project probably should not be more than three, four, five, different types" [5D]
No disruption	0.65	[5D] [7F]	"So we believe that disruption doesn't exist in reality. In reality, it's just the slow pace needs to be managed." [7F]
Safety on-site	0.65	[5D] [7F]	"We started talking about putting sensors and locators on hardhats or high-definition cameras that can analyze the work of the workers to see if they're doing anything risky" [7F]
Alliancing business models	0.56	[3B] [5D]	"I think generally, the contracts are moving much more into alliancing models and we're thinking more about integrators and delivery partners, rather than designer and constructor." [3B]
Design automation	0.56	[3B] [5D]	"The aim… is not to replace the creative aspects of design, but merely to automate the completion of those aspects for which standard processes, designs, and templates already exist." [5D]

Vision 2: User-Data-Driven Built Environment

The cluster in the upper left corner of Fig. 2 forms a second vision for the future, named *user-data-driven built environment*. Interviewees outlining this vision for the future emphasized the importance of ensuring that construction projects be based on actual user data gathered, for example, through sensors in the built environment. Furthermore, interviewees emphasized optimizing the built environment to suit the end user in a sustainable way.

The vision is organized around aspects such as big data, the IoT asset management, sustainability, virtual reality and immersive design, augmented reality on-site and maintenance, IoT energy consumption, end user focus, connected autonomous vehicles and tunnels, and future materials (Table 5).

This future vision focuses on the built environment rather than the construction process. Here, construction companies focus on designing and optimizing the built environment to suit the needs and behavior of users. IoT sensors are installed ubiquitously in the built environment to gather data such as user movement patterns and air quality. The gathered data is combined with other data sources (e.g., weather or climate) in big data sets and used to optimize the utilization of built structures:

> "There's capacity issues. And there are ebbs and flows in the way the system operation. Whether it's raining, or it's not raining, or whether certain trains are in maintenance or in operation. So we can bring it all together to get better insights to an extent that you might be able to say, 'Well, maybe do not schedule a meeting 9:00 AM on a Monday morning in the Fleet Place office, because there's a half chance that six of your invitees might be delayed.' That's the sort of insights that we can generate." [Interviewee 5D - engineering consultancy]

Collected information can be stored in data pools, which create a much more elaborate knowledge base for designing and operating buildings. Instead of relying on building codes and standard information, designers now use the actual use data to dimension built structures to fit specific site conditions and user preferences:

> "For example, when we designed this building, we assumed that if we're going to have, let's say, 55 people on this floor, each of them will use this much water every day, and that means this is the system we need to design for. That's what we do in our [Eurocodes] rule books. No one has actually looked at, actually, in this area with this type of demographic, this type of office use, that actually, we have data that the water usage is this… That's where our design will be informed by much more real data than actually empirical standard information." [Interviewee 5D - engineering consultancy]

User needs are considered as central to the design and new design criteria have emerged. One important design criterion is sustainability, which certain customers consider more important than price and construction time. Sustainability is used to describe not only initiatives aimed at reducing energy consumption and carbon emission of built assets but also the extent to which a built asset improves the quality of life of users (i.e., social sustainability). Construction companies are increasingly interested in the health and well-being of end users, and several companies apply a business-to-consumer (B2C) rather than a business-to-business (B2B) business model:

> "I don't think we'll be building that many roads [in the future]. I think we'll be providing services on the road. So the connected autonomous vehicles will be using data from the road network to improve people's mobility. I think we'll see [Company A] go from a B2B business to maybe a B2C, so we'll be providing services to our clients." [Interviewee 2A - contractor]

Further, the actual interaction with users changes. Construction companies often engage with users by means of VR. The virtual three-dimensional (3D) model of a construction project helps users and designers understand each other during the design phase, as design criteria, suggestions, and alterations are visually tangible within the virtual environment. Consequently, the public hearing phase of construction projects results in far fewer petitions than earlier:

> "If you engage people in the place where you want to innovate, hopefully they'll feel more inclined, hopefully they can see the benefit and hopefully…you can actually say, 'Thank you very much for the research.' Even if it's five years later, you'll feed back to them and say, 'Your innovation was implemented at Euston Station. Come back and rate it.'" [Interviewee 2A - contractor]

VR not only enables involvement of the broader stakeholder landscape, VR experiences can also help users and designers understand highly specific details of the project, such as noise-related aspects of a built structure:

> "When you're in an immersive environment, we can now make it so you can hear how the room will sound based on the different wall coverings, or glass, or ceiling height, or whether the ceiling is exposed, or the floor coverings, or whether there's furniture in there, or whether there are more people in there, and we can model that. So that's when you start getting into the comfort bit." [Interviewee 11J - innovation agency and freelancer]

Finally, the virtual 3D models are also used for augmented reality (AR). Construction professionals on-site use AR glasses or handheld devices (e.g., a tablet) to compare the construction site to the virtual model. Furthermore, AR is used to visualize hidden structures (e.g., water pipes or electricity installations) on-site:

> "Every time there is a problem with a pipe, or any small problem on-site… via the [augmented reality glasses] HoloLens, … you are able to see what's the problem." [Interviewee 1A - contractor]

Consequently, the user focus of this vision is not just targeting end users but includes all users that are a part of the built environment.

Table 5. List of future aspects forming Vision 2: user-data-driven built environment

Future aspect	Centrality	Mentioned by	Quote example
Big data	1.00	[2A] [3B] [5D] [6E] [7F] [9H] [11J]	"You use data with different technologies to make better decisions. So the quicker you can get to making sense of data, the quicker that you'll be able to use technologies to your benefit." [2A]
IoT asset management	0.98	[2A] [5D] [8G3] [11J]	"Looking at the actual assets that's out there… right at this point in time, and get the feedback from that to be able to really optimize the design process, optimize the design parameters" [5D]
Sustainability	0.81	[1A] [2A] [7F] [8G1] [8G3] [9H]	"There are all these…[new] values like sustainability. Your design has to be sustainable. And therefore the fact that it is cheaper and faster is maybe less valuable [to the customer]" [9H]

Virtual reality & immersive design	0.76	[2A] [6E] [11J]	“Engaging the end customer and then taking them into an environment where they share their thoughts. So they can say, ‘Oh, I hate the escalators.’ And then you can say, ‘Okay. Put the goggles on,’ or, ‘Look at the wall,’ and show them the 3D model, ‘You talk us through why you don't like the escalators.’” [2A]
Augmented reality on site and maintenance	0.69	[1A] [2A] [7F] [9H]	“You can effectively take your iPad onto site. When you're turning around on-site, you know whatever element is going where, and you can locate whatever you're looking at” [7F]
Internet of Things (IoT) energy consumption	0.65	[1A] [2A] [5D] [6E] [8G3] [11J]	“The data generated by the operation and how that's actually been brought back to optimizing the performance of those assets so that they use less energy, delivers more value for every pound or euro actually is being investing to that asset.” [5D]
End-user focus	0.50	[1A] [2A] [6E] [8G1]	“I never would have thought there'd be such interest in the health of the occupant 15 years ago. Even though buildings are for people, a lot of designers would say, "Does that pump work? Does that water system work?" in a very technological way. And this trend to focus on the health of the occupant, I think, has happened really quickly. So now, you can talk about health and well-being and still be a respected engineer.” [8G1]
Connected autonomous vehicles and tunnels	0.42	[2A] [10I]	“Connected autonomous vehicles will be using data from the road network to improve people's mobility.” [2A]
Future materials	0.32	[1A] [2A]	”It might be self-healing material in a road environment or bridge environment.” [2A]

Vision 3: Value-Driven Computational Design

The cluster in the upper right corner of Fig. 2 forms the third vision, named *value-driven computational design*. Interviewees outlining this vision for the future emphasized the need for embracing the bespoke nature of construction projects by creating digital designs that simulate the consequences of different design choices and enable changes during the construction process. Moreover, they anticipated a fundamental shift in the organization of construction professionals and profiles of a typical construction company. The vision is comprised of aspects such as digital fabrication on-site, gig economy, design simulations, blockchain, bespoke semiautomation, data-driven companies, distributed off-site production, and digital twin of city (Table 6).

In this vision of the future, all construction projects are bespoke by choice. Construction professionals utilize computational design tools based on AI to simulate the consequences of different design options. Design simulations aid many types of decisions, including not only how the designed structure should look but also how to get materials to the site, how to construct certain parts, and how the project is expected to impact congestion:

> "All the risk sits as soon as you physically buy something, as soon as you physically dig a hole in the ground, all the money sits there. If you can de-risk that and put all of that in the computer, then actually that completely and utterly changes the model for the industry." [Interviewee 4C - management consultancy]

The basic idea is that a digital representation fundamentally changes the way physical infrastructure is developed. Where both the digital and physical can be developed and updated in parallel (in near real time), practitioners talk about a digital twin. A common digital twin of entire cities assists construction professionals in anticipating the impact of built structures on citizen behavior and preferences. Gaming engines and digital twins are used to simulate, for example, evacuation behavior and transport patterns. As user behavior and preferences can be simulated reasonably accurately, the actual end users are disconnected from the design process:

> "We know the way sound will move, and we can pretty much make assumptions about what is uncomfortable and what is comfortable… I mean involving users is great, but most of the time, we involve people so they don't get pissed off that we haven't involved them. They don't actually necessarily give consistent or valid answers." [Interviewee 11J - innovation agency and freelancer]

In this vision, the user is not just involved in the construction process but rather modeled. Despite being modeled, the inconsistencies of actual user needs make construction professionals strive to create flexible designs to cope with changing design criteria and customer preferences during the construction process. This enables the client to commit to design decisions as late as possible. As the client does not need to decide on construction methods until a few days before construction begins, these choices can be based on practical issues, such as site conditions or the availability of workers and machinery on the day in question:

> "You've got to give people the flexibility to take into account the available expertise that's there at that moment in time, to make the decision on what you do next. And to say that we're going to go down a fully automated way, that constrains you just as much as we are now. I think you've got to allow for all the shades in between, and to be able to make a sensible decision." [Interviewee 4C - management consultancy]

The flexibility of design and construction furthermore changes company profiles fundamentally toward more data-driven profiles. Digital skills are now at least as important as traditional construction skills, and the most successful companies are those who have understood how to integrate the two and digitally transform their business model:

> "You want people with a digital skill set working alongside cross people who understand how stuff goes together. And it's all being done in a virtual world. It's not necessarily going to be the contractors of today because their skill set is contracting, setting up

> contracts, and that's not the skill set we really need. We have that skill set because of the disjunct between how well we can design and how well we can build. And so they can fill that gap, whereas actually, if he can solve all those problems on a computer, the contracting side becomes really easy." [Interviewee 4C - management consultancy]

This vision challenges the existing archetypes of companies involved in construction. Instead, the construction sector is characterized by networks of smaller enterprises and freelancers that collaborate on specific construction projects. Typically, each construction stakeholder is hired on project terms for the duration of each project, according to his or her individual contract. In some cases, blockchain-based solutions are used to coordinate between individuals and reduce the need for intermediaries, thus cutting overheads and overall project costs:

> "Why don't we do fixed term contracts? Why don't you hire me for two years to do a piece of work? Why do you feel the need to have me on your books as an employee, and why do I need to work for you five days a week? If the piece of work I'm doing only requires me to do two days per week with you, then I'll do two days a week with you and I'll do two days a week with somebody else. And actually, huge numbers of people would want that flexible way of working." [Interviewee 4C - management consultancy]

This vision is, thus, heavily influenced by the gig economy and the project society, in which people define themselves by the projects they have contributed to rather than the companies they work for. The distributed and flexible workforce is further mirrored in local production facilities spread across the country, providing easy access to, for example, computer numerical control (CNC) machines or laser cutters. By sending a digital BIM model to the nearest production facility, construction stakeholders can create unique items on demand and exploit quick delivery times, thus speeding up the construction process:

> "You would have an individual with a facility, and that facility has a CNC machine, a cutting machine, and additive manufacturing, and… can make all sorts of different things. And that individual is local to where you are building. And so you have hundreds of these individuals all around the UK. And when you have your design, you send that to your local person who will create your flat-pack building or your I-beams or your ductwork or whatever, your modulated system, and ship it to you. And that person, at the same time, could be… printing plastic Christmas trees for a local toy shop. Because all they need is the equipment, and the information is handled digitally, so you're not having these centralized factories that do a specific thing." [Interviewee 11J - innovation agency and freelancer]

The local production is further supported by new digital fabrication methods such as additive manufacturing and robotics. This changes the way in which construction elements are fabricated. Due to the faster and cheaper fabrication technologies, the limitations for what may be designed is changing:

> "So, our kitchen in our house, we've done what's called box in box. There's no hardware. So, there's no runners on our drawers, which is how they used to make cupboards. But they stopped doing it because carpenters couldn't afford to have someone who could make it that precise. A machine can make it that precise. So, we can go back to that style

> of making things. But we've designed so many things in our world based on the limitations of the industrial process… 'We can only make plywood this size because our machine is only this big.' Well, actually we get to rethink all that and say, 'This is the right solution.'" [Interviewee 4C - management consultancy]

Thereby, the flexibility of the production systems enables the bespoke nature of construction projects characterized by this vision.

Table 6. List of future aspects forming Vision 3: value-driven computational design

Future aspect	Centrality	Mentioned by	Quote example
Digital fabrication on site	0.81	[4C] [7F] [8G3] [9H] [11J]	"There's still some things that you have to do on-site, but maybe you could get some automation in there, such as robotics or even additive manufacturing, 3D printing." [11J]
Gig economy	0.79	[4C] [8G1] [10I] [11J]	"I just think that we should be more willing to join the specialists together to deliver a project as opposed to trying to capture them into organizations." [4C]
Design simulations	0.77	[4C] [6E] [9H] [11J]	"This is how people are moving around in this area. How will those people exit? If there is something that happens, that means that we need to get people out within 25 seconds. And, fundamentally, when we do buildings and when we do design, those are the key issues that we start looking at." [11J]
Blockchain	0.77	[4C] [8G1] [11J]	"They're not [supply] chains anymore. They're webs of suppliers, which designers are part of… I think you could with blockchain technologies, potentially." [11J]
Bespoke semi-automation	0.74	[4C] [8G2] [9H] [11J]	"Semi-automization is really interesting, the idea that you can decide as you go along on the right construction methodology... I think when you standardize, you remove options, whereas ... actually, at each point, we could decide which bits we'd put on a CNC machine or a laser cutter and which bits we'd just do in-house [based on the] availability of our carpenter." [4C]
Data-driven companies	0.72	[3B] [4C] [11J]	"If we actually had a Google-like company enter this market, you'd end up with… your fabricators, and your assemblers, and your architects, and your engineers, and your clients all working inside a virtual world to design it all." [4C]
Distributed off-site production	0.59	[11J]	"Can you design your own home and then send that to your local factory, which could be a couple of miles away or in the local city? And then they will have a CNC cutter, and they will cut that." [11J]

Digital twin of city	0.47	[4C] [6E]	"I want a digital twin of London already built and ready to go so that you can do proper analysis of: 'If you put a new Aldi in here, what's the impact on the traffic?'" [4C]

Comparing the Three Visions

The visions differ as they emphasize different primary design criteria, highlight the future potential of different technologies, describe different enabling work processes, and aim toward different overall goals for the sector. Table 7 summarizes the characteristics of each of the three visions for the future of the construction sector. This section will compare and contrast the visions and discuss their implications.

Table 7. Comparison of the three visions

	Vision 1: Efficient construction	**Vision 2:** User-data-driven built environment	**Vision 3:** Value-driven computational design
Task assessment	**BIM:** BIM models are used to contain all relevant data on a construction project to enable seamless transitions between stakeholders.	**Big data:** User data is combined with other data sources to understand user needs and preferences. **IoT:** Data is collected through sensors in the built environments to optimize asset performance.	**Digital twin of city:** Data is compiled in a common city-wide digital twin to enable simulations of the impact of a new construction project.
Design	**Standardization:** Modular and standardized elements are building blocks for design. **Design automation:** Repetitive design tasks have been automated. **AI:** New design tools predict the cost and time of a construction project from an early stage.	**VR and immersive environments:** Stakeholders and end-users explore design solutions in immersive environments. **Sustainability:** User-defined design criteria like sustainability are often regarded as more important than time and cost.	**Design simulations:** Computer-simulated scenarios are used to predict user behavior. **Bespoke semi-automation:** Rather than committing to decisions from an early stage, designers strive to keep open several options for manufacturing and assembly.
Construction methods	**Modularization and off-site construction:** Modular construction leverage the benefits of prefabrication and off-site construction. **Safety on site:** Sensor technology enhances the safety of on-site workers.	**Future materials:** New materials improve the expected life-time of built structures. **AR on site:** On-site workers use augmented reality to compare the virtual model to the actual built structures.	**Distributed off-site production facilities** produce construction elements alongside other manufactured goods. **Digital fabrication methods on site:** Robots and 3D printing technology are used

			on-site and enable customized designs.
Stakeholders and other topics	**No disruption:** Companies are not new entrants but have years of experience from within the sector. **Alliancing business models:** Companies engage in long-term strategic collaborations. **Lean processes:** The work flows are optimized to ensure smooth transactions between construction professionals.	**End-user focus:** Construction companies target end-users using B2C business models. **Connected autonomous vehicles and tunnels:** New types of transportation dominate the built environment.	**Data-driven companies:** Data flows and data management structures form successful construction companies. **Gig economy and blockchain:** Construction workers are organised in project-based networks and hired individually rather than as part of a large company.
Primary aim	Reducing time and cost of construction.	Enhancing the performance of the built environment.	Customizing designs to fit the context.

Centrality of Future Aspects

As can be seen from the network graph in Fig. 2, some future aspects are more highly connected than others. Consequently, these future aspects are found in central locations of the network. The eigenvector centrality measure can be used to calculate the relative importance of each future aspect. The centrality measure considers an aspect important if it is linked to other important aspects. Tables 4-6 rank the future aspects for each vision according to their eigenvector centrality. The future aspect big data turns out to be the most central. This finding is consistent with the general view that implementation of digital technologies relies on good data management. The aspects IoT asset management, off-site construction, AI, modularization, and BIM are also located centrally in the network. All of these future aspects represent Visions 1 and 2, perhaps signaling that the aspects of these two visions are more frequently mentioned (i.e., are better known to the interviewees).

Focus Areas of Each Vision

The three visions are not mutually exclusive, although they have different focus areas (Fig. 3). Whereas Vision 3 focuses on optimizing the design of a construction project, Vision 1 focuses on optimizing construction, and Vision 2 focuses on optimizing for the use phase.

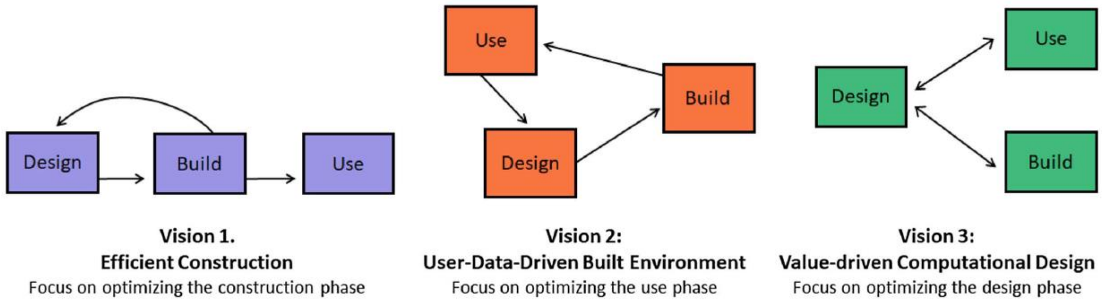

Fig. 3. Visions place emphasis on different parts of the three main phases in a construction project.

Correspondingly, one might think that the interviewees representing contractors are committed to the construction-related aspects of Vision 1, while engineering consultancies are focused on the design-related aspects of Vision 3. However, as can be seen from Table 8, this is not the case.

Table 8. Percentages of the interviewed companies that mentioned aspects from each vision by company type.

Company type	**Vision 1:** Efficient construction	**Vision 2:** User-data-driven built environment	**Vision 3:** Value-driven computational design
Contractors	66%	100%	66%
Engineering consultancies	100%	100%	75%
Small companies	66%	66%	100%

In Table 8, the interviewed companies are differentiated into three company types: contractors, engineering consultancies, and smaller companies (management consultancy, innovation agency, and start-up). Each of these three groups consist of three or four interviewed companies. Contractors and engineering consultancies alike mentioned aspects from all three visions, especially Vision 2. Moreover, smaller companies more consistently mentioned aspects from Vision 3 than contractors and engineering consultancies.

Interdependencies Between Visions

The visions emphasize the potential of various technologies differently. Vision 1 emphasizes the impact of BIM, AI, and off-site manufacturing technologies; Vision 2 emphasizes the impact of big data, IoT, and mixed reality (i.e., VR or AR); and Vision 3 emphasizes the impact of digital twins, design simulation tools, robotics, and 3D printing. Although the visions are in principle self-sufficient, elements from one vision may support or contribute to another vision. For instance, the sensor data described in Vision 2 may be used to improve the design simulations described in Vision 3. In other cases, certain elements from one vision may not be compatible with elements in another vision. For instance, the customized construction elements described in Vision 3 stand in contrast to the modular and standardized construction methods found in Vision 1.

To some extent, it may be difficult to see one vision emerge without future aspects from other visions, as the technological future aspects are dependent on each other. For instance, how would one use virtual reality environments (as described in Vision 2) without a BIM model of the built structure (as described in Vision 1)? In addition, how can a digital twin of entire cities (as described in Vision 3) be created without an immense amount of (big) data from the existing built environment (as described in Vision 2)?

Focusing on similarities between the visions, readers may find it appealing to combine the three visions into one large vision for the future of the sector. Likely, the future will entail a combination of elements from all three visions. However, it is important to keep in mind that the purpose of the visions is not to establish agreement. Instead, the purpose is to explore how different trends and expectations for the future support or conflict with each other, while acknowledging that the future is uncertain.

A company implementing BIM to create lean supply-chain processes will arguably make very different managerial decisions compared with a company implementing BIM to improve its interactions with the client through VR. Similarly, a company seeking to improve its management of big data to optimize the performance of built assets may behave very differently from a company seeking to improve its management of big data to create a city-wide digital twin. Consequently, the authors argue that a company may benefit from clarifying the goal of applying a digital technology. Is the primary aim of implementing new technologies to reduce cost and construction time? To enhance the performance of the built environment? Or to ensure that each design is optimized for its context? Committing to one of the digital visions outlined in this paper could be a way for construction companies to explicate their primary aims.

Contrasting the Visions to Aid Strategic Discussions

The narrative elements of the visions make them useful reference points for discussion. This was demonstrated in Interview 8, which coincidentally had two interviewees who did not share the same vision for the future (although they worked together in the same company). One interviewee (8G1) underlined the importance of standardization and described a future resembling Vision 1, whereas another interviewee (8G2) argued that the future of the sector would include more customized solutions and described a future resembling Vision 3. During the interview, these two interviewees began debating their opposing views on the need for standardization and realized that they had different views on the future of the sector:

> “Imagine if screws and bolts were just random diameters. It’d be crazy… All our references to engineering assembly is based in German standards. So, manufacturing has got to be about standard dimensions. You could still have freedom about how it’s put together, but let’s not play with some of the standardizing principles of manufacturing.” [Interviewee 8G1 - engineering consultancy]

> “My point is that if the future of manufacturing is going to be customization,… Sure, you might start off by standardizing small bits of it, like the screws and the nuts and the bolts. But then get to a point where there are certain aspects of that standardization, which will constrain what you’re doing and if that constraint is so defining that you end up with all student bedrooms looking like exactly the same thing, the market won’t accept that.” [Interviewee 8G2 - engineering consultancy]

By contrasting Visions 1 and 3, stakeholders may find that the future of the sector entails a trade-off between standardization and customization. Arguably, standardization may lead to improved efficiency but also path dependency, thus creating unnecessary constraints for the design. Standardization is typically considered inevitable because it enables automation. However, the current development within AI and digital manufacturing technology may challenge this assumption, as described in Vision 3.

According to Harty et al. (2007), construction futures studies should appreciate the ability of stakeholders to influence some aspects of the future and not others. Comparing the three future visions, construction stakeholders can clarify what parts of the future seem inevitable (e.g., BIM and big data) and what parts are negotiable (e.g., standardization). Comparing the visions, construction professionals may also find it beneficial to discuss when they expect a given future to occur. Some may argue that Vision 1 is likely to happen before Vision 2, or that Vision 2 will be a stepping-stone toward Vision 3. These discussions can be beneficial for construction companies striving to create a resilient long-term strategy.

Innovation Discourses

When envisioning the future, innovation champions are influenced by innovation discourses. These discourses are present in technology-related research exploring what is possible, business-related reports on what is profitable, and policy-making debates on what is desirable. To contextualize the visions, this section will provide an overview of current innovation discourses.

Technology Discourses: What Is Possible?

Most research on the impact of technology on construction tend to focus on single technologies or a group of related technologies and their potential applications. This is the case in, for example, the review by Dainty et al. (2017) of a BIM revolution discourse. Research publications presenting the specific configuration of a technology and its applications may be interpreted as discourses of construction futures. As it is outside of the scope of this article to include all potential technologies, a few categories of emerging technologies were selected based on recent and highly cited articles: automated construction technologies (e.g., Bock 2015), big data (e.g., Bilal et al. 2016), and IoT (e.g., Woodhead et al. 2018).

As an exemplary account of construction futures, Bock (2015) outlines how technologies for automating construction will improve the efficiency of the construction process and transform how buildings are designed. Furthermore, pervasive construction automation technologies will be integrated into the built environment (e.g., in the form of service robots). This, however, imposes disruptive changes on products, processes, organization, management, stakeholders, and business models of the construction sector. Construction automation further connects to other technologies like BIM, 3D scanning, 3D printing, and IoT.

Much research anticipates that big data will have a large impact on the future of the construction sector [e.g., Bilal et al. (2016)]. Mansouri and Akhavian (2018) outline a large number of application areas for big data, including productivity, lean construction, safety, building life cycle management, and sustainability. Madanayake and Egbu (2019) specifically identify sustainability as an umbrella term for organizing the application of big data. In all cases, the implementation of big data entails fundamental changes to either design, production, and/or operational processes (Bilal et al. 2016). Furthermore, the successful implementation of big data connects to the implementation of other technologies like BIM, cloud computing, smart buildings, AR, and IoT.

Focusing specifically on IoT, Woodhead et al. (2018) argue that technologies are typically conceived as singularly focused point solutions and that this perception is counterproductive for the realization of future opportunities. Woodhead et al. (2018) take the point of departure in a future narrative conceptualized as Industry 4.0 and incite that technologies like IoT are seen as an integrated layer - an ecosystem - spanning different parts of construction, processes, organizations and connected systems, and technologies. Specifically, they see IoT connected to topics as BIM, robotics, blockchain, AI, digital twins, and prefabrication. According to Woodhead et al. (2018), a broader mindset of IoT will lead to the introduction of new companies; new smart products; new services; new processes; new ways of working; new expectations; new business models; and new relationships.

Based on this brief review of some on the most cited and recent academic publications on construction technologies, it can be concluded that narratives of construction futures (1) target multiple use cases and areas of applications, (2) are leveraged by connecting multiple different technologies, and (3) entail transformational changes to the industry.

Business Discourses: What Is Profitable?

Over the last five years, an increasing number of highly profiled business publications have articulated a change agenda for construction, arguing that the sector is ripe for disruption (Ernstsen et al. 2018). Inspired by the research by Teicholz et al. (2001) on productivity, the McKinsey Global Institute (Barbosa et al. 2017) argue that the productivity of construction is “remarkably poor” and could be increased by over 50%. The World Economic Forum (2016) adds to this by claiming that the construction industry’s significant economic, societal, and environmental impact creates a substantial case for digitally transforming the sector. Both industry analysis reports highlight the fact that construction may benefit from rethinking regulatory and contractual structures, standardizing work processes, and implementing new technologies. A subsequent article from McKinsey identified rising investments in construction technology firms amounting to $10 billion from 2011 through early 2017 (Blanco et al. 2017). Building upon this insight, Blanco et al. (2018) mapped the existing and emerging applications of digital technologies in a network graph. Their graph revealed four clusters of emerging digital technology in construction: (1) supply-chain optimization and marketplace, (2) 3D printing, modularization, and robotics, (3) artificial intelligence and analytics, and (4) digital twins. Furthermore, Blanco et al. (2018) used the network graph to visualize how the emergence of new digital technology clusters connects to the existing applications of digital technology in construction. While the network graph clearly illustrated the connections and interdependencies between technologies, the analysis did not explore how technology clusters integrate with different visions for the future of the sector.

Policy Discourses: What Is Desirable?

Governments facilitate the adoption of digital technologies in construction through various policy instruments and strategies (Blanco et al. 2019). In the UK, a widely accepted policy narrative describes the construction sector as lagging behind other sectors and needing modernization. The corresponding improvement agenda, which was introduced by the Rethinking Construction report (Egan 1998), has been discussed in the literature as a performative discourse that seeks to promote improved competitiveness and sectoral efficiency (Green et al. 2008; Sergeeva and Green 2019).

From this perspective, construction policies are shaped in a dynamic negotiation and competition between multiple discourses (Green 2011). The dominant performative discourse exists as it positions itself in contrast to other discourses. A significant, concurrent counterdiscourse may, for example, describe the need for promoting sustainability of the built environment (Akadiri and Fadiya 2013; Pomponi and Moncaster 2017). This counterdiscourse focuses on minimizing the negative environmental side effects of production and consumption, and draws on the concepts of circular economy and sustainable supply-chain management (Nasir et al. 2017). Other counterdiscourses emerge and consolidate or disappear over time. Research has, for example, also articulated and discussed an adaptive architecture discourse (Cheng and Bier 2016).

Recently, Sergeeva and Green (2019) highlighted a need for introducing nuance into the dominant construction sector narrative. Furthermore, they identified a need for empirical research that explores how construction practitioners interpret innovation. Through qualitative analyses of interviews with innovation champions, two studies have found that champions draw on sectoral narratives or discourses in their descriptions of past and present innovations (Leiringer and Cardellino 2008; Sergeeva and Green 2019). Consequently, researchers studying construction innovation can benefit from considering innovation to be a constituent part of wider discourses in the sector (Leiringer and Cardellino 2008). The three visions for digital transformation of construction should be seen from this perspective.

Situating the Visions in Current Innovation Discourses

The following section will put the visions *efficient construction, user-data driven built environment*, and *value-driven computational design* into perspective by investigating their alignment with current technology, business, and policy discourses.

Alignment with Technology Discourses

The visions connect to broader technology discourses on what is technically possible. Three dominant technology discourses were presented in the previous section: construction automation, big data, and IoT. It is thus interesting to investigate how the visions align with the existing discourses on technology in construction.

The technology discourse on construction automation presented in, for example, Bock (2015) connects construction automation to Visions 1 and 3 through the future aspects design automation, standardization, digital fabrication on-site, and bespoke semiautomation. While this is in line with the predominant discourse on automation, it is challenged by Bock’s (2015) idea that automation is not just about improving the efficiency of construction but targeting the broader built environment (Vision 2).

The technology discourse on big data claims that big data implementation entails a large number of changes to construction sector processes and points out that big data connects to a large number of other technologies (Bilal et al. 2016). The centrality of the big data node in the network in Fig. 2 supports this claim, stating that implementation of big data seems to play a pivotal role in most visions for the future of construction.

The current technology discourse on IoT is primarily connected to Vision 2, as it entails the collection of data through sensors in the built environment to optimize asset performance. However, the broader conceptualization proposed by Woodhead et al. (2018) also connects this technology discourse to Vision 1 (BIM and robotics) and Vision 3 (blockchain, AI, digital twins, and prefabrication).

These accounts of technological discourses suggest that technologies are much more interdependent than what is usually considered. The technologies connect to a wide range of complementary technologies and areas of application. The network graph (Fig. 2) confirms this. The technology discourses on IoT and construction automation articulate a broader area of application than what is currently formulated by the innovations champions. This suggests that visions can be further informed by technological possibilities. Conversely, the visions establish a framework of potential (desirable) futures, which can inform further research into technological possibilities.

Alignment with Business Discourses

The visions also connect to global business discourses. The network graph developed by McKinsey (Blanco et al. 2018) provides an overview of the many existing and emerging technology solutions provided by IT companies in construction. A comparison of this network and the network presented in Fig. 2 reveals a number of shared nodes (future aspects), including BIM, off-site fabrication, automation, and AI. The similarities between the two networks suggest that the future narratives of innovation champions affect (or are affected by) emerging application examples of digital technology within the sector. However, it is important to note that the two networks represent different perspectives on the transformation of the construction sector. The overview identified by McKinsey explicitly targets the productivity challenge in construction. While this fits very well with Vision 1 and the pursuit of construction efficiency, it only represent a subset of potential futures as highlighted by the focus of Visions 2 and 3.

In a larger perspective, the previous comparison and the identified similarities and differences suggest that there is room for further research into the configuration of technologies, organizations, and visions.

Alignment with Policy Discourses

Finally, the visions have implications for policy makers. This research suggests a multiplicity of coexisting visions for digital transformation of construction that are more or less represented in, and aligned with, policy discourses. The interviewees' notions of the future are shaped by, and also shape, this wider ecology of practice, with each interviewee's view on the future informed and inspired by conversations with other construction professionals. In this way, the three visions represent overlapping and competing agendas, which are, to some extent, accommodated within the negotiated policy discourses in the UK construction sector.

The notion of *efficient construction* (Vision 1) is a theme in post-Egan policy discourses in construction, which treat the sector as poor in productivity, and compare it unfavorably with the car industry. The targets in the Construction 2025 document (HM Government 2013) suggest the need for a 33% reduction in the cost of construction and the whole life cost of assets; and a 50% reduction in the time taken from inception to completion of new build - targets that suggest the need for efficient construction.

Vision 2 connects to a rising sustainability discourse in the UK construction sector. Construction represents one of the most resource-intensive sectors, accounting for 50% of the UK's carbon emissions and 50% of its water consumption (Akadiri and Fadiya 2013). Striving to reinforce better management of resources, researchers and policy makers have acknowledged the potential for reducing the environmental impact of the sector by reducing energy use and waste production of the built environment (Pomponi and Moncaster 2017). The industry has set ambitious targets for a 50% reduction in greenhouse gas emissions in the built environment—supporting the Industrial Strategy's Clean Growth Grand Challenge (HM Government 2017). This is further supported and challenged through the growing adoption of certification schemes and circular economy (Pomponi and Moncaster 2017).

Vision 3 connects to the work of the National Infrastructure Commission report on Data for the Public Good, which set out the idea of a national digital twin (National Infrastructure Commission 2017). However, it also challenges some of the established truths that currently drive innovation in construction, proposing, for instance, that standardization is not a necessary condition for obtaining efficient production processes and that user involvement is not needed to create user-centered value. The elements of Vision 3 represent one or more emerging counterdiscourses, such as the one Cheng and Bier (2016) call adaptive architecture. These emerging discourses can challenge policy makers and construction practitioners to think differently about the future and explore alternative, uncharted ways of getting there. The findings from this study (Table 8) suggest that small companies are more likely to commit to emerging counterdiscourses (corresponding to those of Vision 3). In contrast, the larger companies interviewed tended to refer to established discourses connected to Visions 1 and 2. The multiplicity of visions illustrates how counterdiscourses can challenge or consolidate current policy development while stimulating discussions about the preferred future of construction. When visions are incompatible, Jensen et al. (2011, p. 665) suggest that the "most productive governance response may be to recognize and accept their conflicting strategic implications." Policy makers may compare and contrast the visions to understand how regulatory instruments may support or hinder various preferred outcomes. This may support reflective policy making, which acknowledges the ambiguity and conflicting interests involved in transforming the sector to what is desirable for society.

Directions for Further Research

This study reveals multiple visions that innovation champions have for the future of digital construction. From the interview data, three visions have been identified. As such discourses are in flux, further research may build on and extend this work to identify additional, or differently configured, visions for the future.

The three visions describe unknown futures and are therefore inherently difficult to validate. It may be appealing to strive for validation, for example, by asking construction stakeholders to select the most plausible, desirable, or likely future. However, it is important to note that the results of such a ballot would not reflect the actual likelihood of each future occurring. On the contrary, the results of a ballot might divert construction stakeholders to consider, discuss, and plan for only one possible future. To be resilient in a changing market, construction professionals and policy makers should instead strive to consider several possible future outcomes. The three visions may constitute a narrative reference point for this kind of strategic discussion.

As innovation champions, and therefore promoters of innovation, the interviewees are likely to be affected by pro-innovation bias. As a result of such a bias, the interviewees may—more or less deliberately—emphasize positive elements of the future and downplay potentially negative side effects. Similar interviews with late adopters of innovation would presumably change the outcome of the study significantly.

By creating visions, this study presents positive descriptions of the future that may be used as guidance when construction stakeholders seek to create change in the sector. However, to operationalize the visions, these stakeholders may also benefit from identifying the potential barriers and pitfalls involved in implementing the visions. Further research could identify these implementation challenges and propose ways to mitigate related risks.

Whereas foresight methods are useful for exploring the future, the subsequent implementation of a desired future is better described by innovation management research. To operationalize the visions, further research could therefore benefit from connecting practitioner’s expectations for the future to theory on construction innovation. The literature on systemic innovation may, for example, be used to investigate how rapidly various technologies can be expected to diffuse in the sector, and the literature on disruptive innovation may qualify discussions about how construction companies could and should respond to this. The presented visions provide a platform for further research on how digital technologies may aid transformative changes in construction.

Summary and Conclusion

To improve the performance of the construction sector, innovation is essential. Previous studies have demonstrated that innovation champions are vital drivers of innovation, as these individuals influence other stakeholders by means of compelling narratives or visions for the future. This paper has explored possible futures of the construction sector from the perspective of construction innovation champions and their narratives around digital technologies. Interviews with 13 innovation champions revealed three distinct future visions: (1) efficient construction, (2) user-datadriven built environment, and (3) value-driven computational design. The three identified visions are not exclusive but show that multiple visions emerge and are negotiated by innovation champions in envisioning the future. A theme shared by all visions is that digital technologies play an important role in all of these envisioned futures of construction, although the technological potential manifests in different ways. The visions illustrate how a combination of multiple digital technologies may change the way in which structures are designed and fabricated, who the main stakeholders of construction are, how professionals collaborate, and how important various design criteria are.

This study contributes to construction future studies, as it describes multiple ways in which a combination of technologies and trends affect the sector. Furthermore, the study contributes to the literature on innovation discourses, as it connects the visions of innovation champions to the concurrent sectoral debates of construction. The findings suggest that innovation champions’ narratives for the future are influenced by wider innovation discourses. These discourses consider what is technologically possible, profitable in a business context, and desirable on a societal level. The paper thus contributes to research, practice, and policy, as a holistic understanding of possible futures may help construction professionals in deciding how to stimulate transformational change that is possible, profitable, and desirable.

Data Availability Statement

Some or all data, models, or code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions. Interview transcriptions contain anonymized information about the names and company affiliation of interviewees.

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Ernstsen, S. K. N., Thuesen, C., Mossing, C., Brinck, S., & Maier, A. (*under review*). Technology Cards: A design game for navigating in a future of digital technologies. International Journal of Design.

Appendix D: The Technology Cards Paper

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Technology Cards*: A design game for navigating in a future of digital technologies*

Digitalisation has a game-changing effect on society. However, researchers and practitioners find it difficult to grasp the potential implications of digital technologies. Design games are well known for their ability to make abstract concepts, such as digitalisation, tangible. In this paper, we introduce the *Technology Cards* – a dialogue-based design game that allows users to explore the impact of multiple technologies on their future business. We review 14 card-based design games focusing on emerging technologies and/or futures thinking and identify an unmet need for design games that help business managers navigate in a digital future. Next, we describe the development of the *Technology Cards* and their testing in 17 *Tech Session* workshops with 257 participants from 40 organisations. The findings reveal that the *Technology Cards* are 'instruments of inquiry' that aid users in a) framing current challenges, b) imagining how multiple technologies affect the future, c) identifying synergies between technologies, and d) facilitating constructive dialogue. Although the *Technology Cards* were designed specifically for the construction sector, the findings suggest that they are relevant across sectors. We discuss the importance of involving non-technology-savvy stakeholders in envisioning digital futures and demonstrate synergies between the fields of design and futures studies.

Keywords **–** Construction Sector, Design Game, Design Tools, Digital, Future, Technologies.

Relevance to Design Practice **–** The *Technology Cards* design game facilitates constructive dialogue on how multiple technologies will affect the future. The paper demonstrates how practitioners can use the card deck to discuss the implications of digitalisation and to prioritise strategic actions.

Introduction

Digital technologies have changed how we communicate, travel, interact, shop, entertain ourselves, and do business. Digitalisation is a powerful process, as it detaches information (such as text or voice) from its physical storage (such as a letter or a CD), and also its transmission and processing technologies (such as postal services or CD players) (Tilson et al. 2010). This detachment from physical assets makes digital technologies applicable and relevant in any sector of society. However, the detachment from physical assets also makes the potential of digital technologies abstract and intangible for stakeholders. Consequently, the implications of digital technologies for society can be difficult to comprehend and foresee.

For business managers, anticipating potential implications of digital technologies is a critical challenge. This challenge is exacerbated by the speed of change and the vast number of technologies that are emerging and evolving. For example, *internet of things* may provide companies with real data on user behaviour, *virtual and augmented reality* may be used to create immersive customer experiences, *artificial intelligence* may be used to optimise the operation of assets, *3D printing* may enable new production methods, or *robotics* may be used to improve efficiency in the supply chain. For each of the many new digital technologies, there are numerous application opportunities, affecting all aspects of business and design processes.

Often, digitalisation is approached from a purely technical point of view (De Roeck et al. 2014). This said, we find that design researchers increasingly consider technological opportunities in connection with societal and contextual considerations. For example, Coskun, Kaner, and Bostan (2018) studied how smart home technology affects future user preferences, and Joseph, Smitheram, Cleveland, Stephen, & Fisher (2017) studied how emerging smart textiles have induced a need for new methodological approaches that support functionality as well as fashion and embodied interaction. Other design researchers have studied the intangible aspects of digital technologies. For example, Kleinsmann and Bhömer (2020) proposed that designers should use new types of prototypes to grasp the intangible aspects of digital product service systems. And Nam and Kim (2011) proposed a new design method called Design by Tangible Stories, which utilises gamification elements to help designers create meaningful digital products. These studies found that design processes improve when 'digital' aspects are made relatable and tangible.

In this paper, we presents a future-oriented design game, called *Technology Cards*. The design game presents 22 high-impact- and predominantly digital technologies. To ensure that the technologies are relatable and tangible for people, we developed the *Technology Cards* with one specific application domain in focus: the construction sector.

Construction is one of the largest sectors of society – constituting 9 % of EU's gross domestic product (European Commission 2016); and it also so happens to be one of the least digital sectors of society (Gandhi et al. 2016). The construction sector, which includes large infrastructure, is concerned with planning, procuring, designing, constructing, renovating and operating physical structures in the built environment. Most construction projects involve a large number of stakeholders, including architects, engineers, contractors, suppliers, clients, and investors. Considering the complex stakeholder network, work processes and contractual structures of construction, several industry analysts and researchers have highlighted a significant potential for enhancing the productivity of the sector and call for digital transformation or disruption (Barbosa et al. 2017; Ernstsen et al. 2018a; World Economic Forum 2016). Although construction stakeholders generally acknowledge the potential benefits of digital technologies, they struggle to understand which technologies to implement and how (Lavikka et al. 2018). Here, we see design games play an important role.

The paper is structured in the following way. First, we consult literature on design and futures studies and review 14 card-based design games that focus on new technologies and/or futures thinking. Second, we introduce the *Technology Cards* and present the four criteria used for selecting the 22 technologies depicted on the cards. Third, we describe the iterative process of developing and evaluating the card deck. Fourth, we highlight the findings from testing the cards in 17 workshops (*Tech Sessions*) with 257 participants. The findings demonstrate how the *Technology Cards* aid business managers in exploring the future by a) framing current challenges, b) imagining how multiple technologies may affect the future, c) identifying synergies between technologies, and d) facilitating constructive dialogue. Finally, the paper discusses limitations of the card deck, the implications for research and practice, and points towards avenues for further work.

A future-oriented design approach

To aid business managers in navigating an increasingly digital market landscape and deciding on appropriate action, this paper applies a future-oriented design approach. Design and futures studies are two intersecting, converging and to some extent overlapping research fields (Ollenburg 2019). Both fields are concerned with exploring and forming aspects of the future, and both fields involve multiple stakeholders in creating and/or anticipating the future. According to Dalsgaard (2017 p. 24),

> "design can be seen as a field concerned with finding novel and useful ways of approaching and transforming uncertain situations in which there are no straightforward answers."

In other words, a design approach can help stakeholders understand the complexity of an uncertain situation and create means to improve the situation. The field of futures studies can contribute to the design process, as it explores the conditions for design – and emphasises the need for considering multiple possible futures. According to Kreibich, Oertel, & Wölk (2011 p. 1)

> "Futures studies are the scientific study of possible, desirable, and probable future developments and scope for design, as well as the conditions for these in the past and in the present."

Participatory approaches are central in design and in futures studies. Whereas futurists tend to engage stakeholders through, e.g., road-mapping activities or scenario creation (Popper 2008), designers tend to engage users in design processes, e.g., by means of artefacts as media (Crilly et al. 2008), including prototypes (Kleinsmann and Ten Bhömer 2020) or design games (Lee et al. 2020). All of these participatory methods aim to facilitate constructive dialogue between stakeholders from various backgrounds and explore intangible and uncertain aspects of the future.

Design Games – theoretical framing

Design games as instruments of inquiry

Design games, and in particular *card-based* design games, have become increasingly popular within the last decade (Peters et al. 2020). Acting as boundary objects between stakeholders in a design process, design games can set rules for collaborative activities and bring in new perspectives (Kwiatkowska et al. 2014). Design games have been developed for a number of different purposes, e.g. for investigating a design problem (Belman et al. 2011), influencing user behaviour (Lockton et al. 2010), facilitating collaboration (Brandt and Messeter 2004), or generating ideas (Friedman and Hendry 2012).

The strength of design games includes their ability to 1) facilitate creative combinations of information or ideas, 2) summarise useful information, and 3) provide a common frame of reference for communication among the participants (Roy and Warren 2019). Furthermore, the physical gestures involved in e.g. holding, moving and grouping cards can aid cognition and help simplify the complexity of a design problem (Clatworthy 2011).

Design games fall within the category of design tools. Dalsgaard (2017) characterises design tools as "instruments of inquiry" that possess one or more of five basic qualities:

- Perception: revealing otherwise hidden facets of a design situation (and obscuring other facets),
- Conception: helping designers understand the problem(s) and examine possible solutions,
- Externalization: making imagined design solutions part of the world to allow for evaluation,
- Knowing-through-action: generating new knowledge through acting with an instrument, and
- Mediation: allowing actors and artefacts to exchange insights and coordinate actions.

Taking Dalsgaard's proposition, we investigate to what extent design games in the form of *Technology Cards* elicit perception, conception, externalization, knowing-through-action, and mediation.

Technology-oriented design games

Reviewing 76 analogue design tools for collaborative ideation, Peters et al. (2020) found that the majority (72 %) were, or included, card decks. They also found that the number of card-based design games had grown significantly within the last 10 years. However, despite the increasing number of design games, only four out of 76 focus on digital technologies. We reviewed these four technology-oriented design games identified by Peters et al. (2020) (see Table 1) and discovered a need for playful imagining of combinatorial technology innovation.

Table 5: Technology-oriented design games

	Card deck	*Year*	*Author*	*Content*	*Purpose*	*Activity*
A	**Intelligence Augmenta-tion Design Toolkit**	2017	Futurice (2020a)	60 cards of four types: channel/touchpoint cards, machine learning interaction cards, customer segments cards, and unexpected bug cards. A map, two canvasses and a booklet.	To teach non-tech experts to design future smart concepts.	Creating concepts for using machine learning. Prototyping.
B	**IoT Service Kit**	2015	Futurice (2020b)	Five types of cards: sensors, interactions, service cards, open APIs, and user cards. Tokens that represent users, vehicles, and assets. Maps.	To co-create user-centric IoT experiences.	Designing user journeys. Mapping interactions.
C	**KnowCards**	2014	Aspiala & Deschamps-Sonsino (2020)	162 cards with simple descriptions of components in four categories: input, output, power and connection	To learn about IoT components and aid the design of new products.	Learning about components. Analysing current products. Brainstorming new use cases.

D	**Mixed Reality Game Cards**	2016	Wetzel et al. (2017)	51 opportunity cards, 18 question cards, 24 challenge cards.	To create and develop ideas for mixed reality games.	Generating ideas. Developing ideas. Documenting ideas.

The technology-oriented design games from Table 1 focus on ideation and development of technological solutions for the future. The games are well suited for exploring how digital technologies can be applied in practice. As described by De Roeck, Stappers, and Standaert (2014), digitalisation has created an emerging need for these kinds of ideation and conceptualisation tools, which aid the design of connected products and help the designer consider and combine physical and digital aspects of a service. Each of the games listed in Table 1 unfolds the potential of one of three digital technologies: Machine learning, internet of things (IoT) and mixed reality.

Although the four games provide a comprehensive overview of the opportunities provided by a specific technology, they do not consider combination of multiple technologies or include other emerging technologies such as *autonomous vehicles* or *generative design*. To aid business managers in grasping the implications of digitalisation, we strive to imagine how digital technologies in combination will affect the competitive landscape of their business. Instead of considering ideation games, we therefore focus attention on another branch of design games, namely those aiding futures thinking.

Design games for futures thinking

Roy and Warren (2019) reviewed 155 card-based design tools and classified them in six categories: creative thinking and problem solving; domain-specific design; human-centred design; systematic design methods and procedures; team building and collaborative working; and futures thinking. Only seven card decks (4.5 %) ended up in the category of futures thinking. A similar review by Peters et al. (2020) identified four card-based tools in the category of futures thinking, of which three were not on the list of Roy and Warren (2019). This yields ten design games that aid futures thinking (see Table 2).

Table 6: Design games on futures thinking

	Title	*Year*	*Author*	*Content*	*Purpose*	*Activity*
E	**Envisioning Cards**	2002	Friedman & Hendry (2012)	28 cards in four categories: Stakeholder, Time, Values, Pervasiveness.	To consider human values during design processes.	(Re)framing a design problem. Exploring the solution space.
F	**Drivers of Change cards**	2006-9	Arup Foresight (2020)	An app and multiple physical card decks. 10 categories: climate change, convergence, energy, demographics, oceans, water, food, waste, poverty, urbanisation.	To identify and explore leading factors affecting the future.	Facilitating conversations about trends shaping the future. Informing business strategy, brainstorming and education.

G	**Foresight Cards - STEEP Edition**	2012	IVTO - A future strategy company (2020)	125 cards in 5 categories: social, technological, economic, environmental and political.	To identify and explore leading factors affecting the future.	Understanding how developments in the external environment affect e.g. market conditions and business models.
H	**Liberating Voices cards**	2011	Public Sphere Project (2020)	136 pattern cards describing different aspects of social change.	To promote social change all over the world.	Addressing information or communication problems.
I	**The Thing from the Future**	2015	Situation Lab (2020)	108 card in four categories: Arc, Terrain, Object, and Mood.	To spark imagination about products of the future.	Facilitating creativity and entertainment.
J	**Design Fiction Product Design Work Kit**	2012	The Near Future Laboratory (Girardin 2015)	52 cards in three categories: Design action, Attribute and Object.	To spark imagination about products of the future.	Facilitating creativity.
K	**Triggers: a powerful ideation tool - Innovation Deck**	2016	Triggers (2020)	60 cards with trigger questions.	To facilitate idea generation processes.	Collaborative brainstorming of ideas.
L	**Human-centred Design prompt for emerging technologies**	2017	Google Play & IDEO (2017)	20 cards with prompts for 4 technologies: virtual reality, augmented reality, digital assistant, ephemeral apps.	To facilitate idea generation processes.	Brainstorming ideas from user scenarios and prompts.
M	**FutureDeck**	2015	Gerenwa (2020)	126 cards with growth markets, impacts, technologies	To facilitate idea generation processes	Collaborative brainstorming of ideas.
N	**IMPACT: A Foresight Game**	2016	Idea couture (2020)	A board game with 10 domains of society, a stack of impact cards with technological events, persona cards and cubes.	To think critically about how emerging technologies can impact society.	Learning about emerging technologies. Imagining future implications of emerging change.

Although the ten games in Table 2 all fall within the category of futures thinking, they serve different purposes. Similarly to the design games in Table 1, the majority of the future thinking games focus on idea generation and conceptualisation (I, J, K, L, M). Another group of games focuses on promoting better designs or change (E, H) and a third group focuses on anticipating the impact of trends and technologies (F, G, N).

The *Technology Cards*, which we will introduce in this paper, fall within the third of these three groups, namely anticipating the impact of trends and technologies. This third group contains three games: The *Drivers of Change Cards*, the *Foresight Cards – STEEP Edition* and *IMPACT: A Foresight Game*. The first two both present a number of trends by applying the STEEP framework (social, technological, economic, environmental and political trends). The third game, *IMPACT: A Foresight Game* is the only game in Table 2, which focuses on the combined future impact of new technologies. This is also the only game that is not purely based on cards. It is a board game that has the players compete to secure the future job of their persona, while multiple technological events occur. While this game provides an overview of the implications of different digital technologies, it is played with a number of hypothetical personas. The game does not challenge the players to think of technological implications for their real-world business.

Correspondingly, we find that there is a need for design games that allow the users to explore the combined impact of multiple new technologies on the future of their business. In the following section, we will present the *Technology Cards*, a versatile card game that can facilitate strategic dialogues on future implications of digital technologies.

Introducing the *Technology Cards*

To strategically navigate among multiple new technologies, companies do not need extensive technical knowledge of all technologies. Neither do they need the ability to explain the difference between two closely related technologies such as *deep learning* and *machine learning*. Instead, we propose that a comprehensive overview of all the technological possibilities that may affect their future is needed. Therefore, a full deck of *Technology Cards* strives to present all relevant technologies that construction companies need to take into consideration to prepare for a digital future.

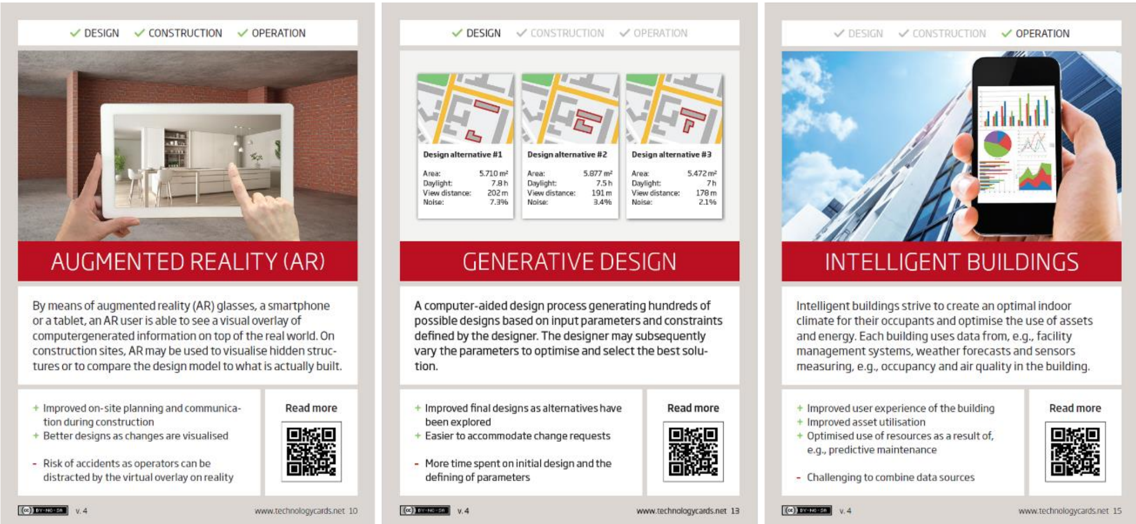

Figure 16. Three of the 22 *Technology Cards* (www.technologycards.net)

Each card presents a technology in a straightforward, playful manner by means of an image, short descriptive sentences, and a short list of benefits and challenges of the technology (see Figure 1). Moreover, a design element at the top of the cards shows the expected implications on the construction process, i.e. whether the technology contributes primarily to the design phase, construction phase and/or operation phase of a typical construction project (the three phases are found in Motawa, Price and Sher (1999)). The cards are designed to enhance playability by minimising the amount of text on the cards. A QR-code is added to give people using the card direct access to a webpage (www.technologycards.net) with detailed information on each technology.

Selection Criteria

Technology is a term that is commonly understood by most, yet ill defined. Technology may be both material (such as a car) and immaterial (such as virtual computing), and technology can be simple (such as a sensor) and complex (such as artificial intelligence). Furthermore, technology can be an artefact, a creation process and a human practice (Digironimo 2011). In this paper, we draw on a basic definition proposed by Arthur (2009). He states that “technology is a means to fulfil a human purpose”, and that a “means” can be a method, process or device (Arthur 2009 p. 28).

Using this rather broad definition of technology, we approached the technology identification process open-mindedly and identified 133 technologies from across all sectors of society (Ernstsen et al. 2018b). We aimed at creating a deck of cards that was representative of all the important technologies approaching construction, while ensuring that the deck of cards had a manageable amount of cards, so that one could go through all the cards in one game. We therefore iteratively developed the selection criteria, while we practice tested initial versions of the card deck and compared our experiences to the insights found in foresight, disruption and innovation management literature (Christensen 1997; Gans 2016; Henderson and Clark 1990; Phaal et al. 2011).

Selecting the final deck of 22 technologies, we applied the following four selection criteria: domain relevance, demonstrated applicability, game-changing potential and concrete application (described in detail in the following four sub-sections). Whether or not the technology was digital was not a part of the initial selection criteria. However, the final selection of technologies reveals that only one out of 22 technologies were not (fully or partially) digital: *Advanced building materials*. The remaining 21 selected technologies are: *Agent-based modelling and discrete event simulations; Artificial intelligence predictions; Augmented reality; Autonomous construction vehicles; Big data analytics; Blockchain; Building information modelling (BIM); 4D, 5D and 6D BIM; Cloud-based construction management; Construction 3D printing; Construction robots; Drone survey; Generative design; Industrial exoskeletons; Intelligent buildings; Linked data for buildings; New building materials; Prefabrication and modular construction; Reality capture; Smart cities; Smart construction site;* and *Virtual reality* (Figure 2). The four selection criteria are described in detail below.

Domain relevant technologies with the potential to replace current construction products

To ensure that the selected technologies are relevant to construction stakeholders, we looked for technologies that have the potential to replace other products or services currently offered by construction companies. While DNA sequencing and brain-computer interfaces are technologies with significant impact on the future of society, we do not expect these technologies to have an immediate effect on construction. For the same reason, connected autonomous vehicles (CAVs), for example, were also not included in the current deck of Technology Cards. CAVs will likely change the design of the built environment (e.g. so that hop-on/hop-off spots are preferred over parking lots) but they do not directly replace any of the existing construction products and processes. According to Gans (2016) the replacement effect is important, as it induces switch-over costs, which can make established companies reluctant to adopt new technology.

Technologies that have been demonstrated applicable in construction

All technologies evolve over time. According to Phaal et al. (2011), this evolutionary process can be split into four phases: science, technology, application, market. A new science becomes a technology, when it is “sufficiently robust to be integrated into a functional system” (Phaal et al. 2011 p. 221). However, at this point in time, the performance and commercial applicability of the technology is still uncertain. To ensure that we select technologies that are applicable in the construction domain, we defined a selection criterion that favours technologies that have matured enough to have passed the threshold of “application demonstrator” (Phaal et al. 2011).

Technologies with a game-changing potential

To foresee major changes (e.g. disruption) in the construction sector, we were especially interested in identifying technologies that can act as game-changers. Christensen (1997) defines disruptive technologies as “very much different” from the existing alternatives. Henderson and Clark (1990) argue that architectural innovations are especially powerful as they can reconfigure the relationship between components and hereby restructure the relationship between organisational units. We use the term ‘game-changers’ to encompass both of these descriptions of novelty. We look for game-changing technologies that are very much different to existing value propositions offered by construction companies and/or that reconfigure sectoral structures by combining existing components in a new way.

Concrete applications

To ensure that the *Technology Cards* are playable and relatable, we search for concrete applications of each technology. Rather than letting a card present an abstract technology such as “internet of things”, we have specified three cards that present concrete applications of internet of things, i.e. “intelligent buildings”, “smart construction site” and “smart city”.

The Selected 22 Technologies

The *Technology Cards* present 22 technologies, which are listed alphabetically in Figure 2.

Agent-based modelling and discrete event simulations Artificial intelligence predictions Augmented reality Autonomous construction vehicles Big data analytics Blockchain Building information modelling (BIM)	4D, 5D and 6D BIM Cloud-based construction management Construction 3D printing Construction robots Drone survey Generative design Industrial exoskeletons Intelligent buildings Linked data for buildings	New building materials Prefabrication and modular construction Reality capture Smart cities Smart construction site Virtual reality

Figure 2. The 22 technologies depicted on the *Technology Cards*.

The selection of technologies aims to be representative of all the technologies that are relevant for construction companies to consider. However, the relevance of a technology is greatly dependent on the context. Therefore, we incorporated two empty cards into the deck to allow users to add a technology of their own choice. To make a complete deck of *Technology Cards*, we also added a box and two extra cards explaining the purpose of the cards and how to use them. The cards are A6 size (105 x 148 mm) and printed on thick paper (300 g), similarly to a traditional deck of cards.

Method

The *Technology Cards* were designed through an iterative process, in which we tested and redesigned the cards several times (see Figure 3)

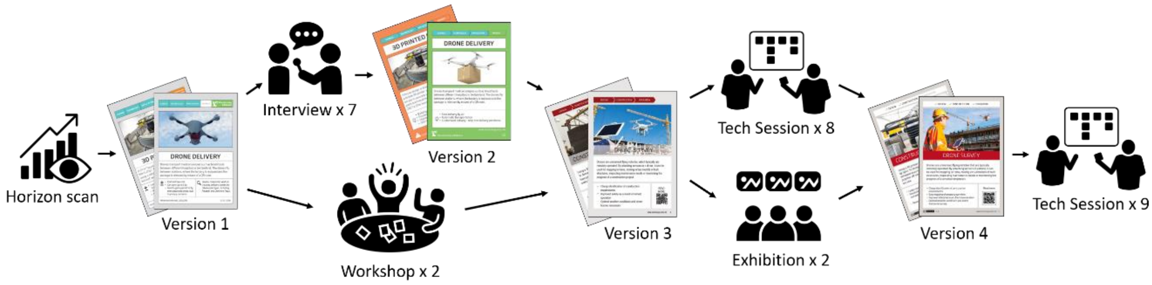

Figure 3. The *Technology Cards* were designed through an iterative process

Technology Cards version 1 and version 2

We conducted at horizon scan and identified the afore mentioned 133 cross-sectoral technologies in reports and conferences. The first two versions of the cards presented 26 technologies from across 6 sectors: construction & transportation, digital economy, healthcare and biogenetics, information technology, manufacturing and robotics, and space. The selection of 26 initial technologies were driven by curiosity and a desire to have as many different domains represented as possible.

Testing the design of the cards through interviews

To test the initial card design, we conducted seven 30-minute interviews with construction sector practitioners. We showed the interviewees five different designs of the *Technology Cards* and asked them to design the perfect card, e.g. by choosing one of the five designs or by combining parts of the different designs into one card. The results from these interviews led us to redesign the cards and create card version 2.

Testing the use of the cards through workshops

To test the usability of the cards, we held two workshops with 11 participants in total, including 7 construction practitioners and 4 engineering students. The purpose of both workshops was to create ideas for how a construction company could benefit from applying the cross-sectoral technologies depicted on the cards. First, we asked the participants to create “domain cards” representing their own fields of work, inspired by Halskov and Dalsgaard (2006). Second, we divided the participants into groups and had them identify the main technological principles from one or more *Technology Cards*. Third, the groups created new ideas by transferring the technological principles from the cards into their own domains. Finally, the groups presented their ideas in plenum and evaluated the workshop.

Feedback from the workshops revealed that the participants were intrigued and inspired by the concept of the cards. However, they found the ideation exercises difficult, as it was hard to extract the main principles from one domain and apply it in another. The participants struggled with imagining how the technological principles of e.g. gene editing (CRIPR/Cas9) technology or small satellites could be useful in the construction sector, and this constrained the ideation activity. Furthermore, we observed an urge among the participants to combine several cards instead of working with one at a time.

Reframing the purpose of the Technology Cards

The interview results and the workshop evaluations led us to reframe the purpose of the *Technology Cards* to focus on strategic dialogue rather than on creativity. We had assumed that the main advantage of the cards would be to facilitate ideation, but actually, the cards were better suited for stimulating dialogue and gaining an overview of how multiple new technologies will affect the future. This represented a major junction in the development of the cards and way of playing. Furthermore, we decided to redo the selection of technologies depicted on the cards to ensure that the technologies were relevant to construction. Correspondingly, we redesigned the cards and the workshop format to encourage browsing through all the cards and to allow for combining several cards.

***Technology Cards* version 3 and version 4**

The third and fourth version of the *Technology Cards* present 22 technologies that are relevant to the construction sector. As the point of departure for the technology selection, we used a recent report from the World Economic Forum, Future of Construction Initiative, which lists 10 of “the most promising digital technologies for improving productivity in the industry” (World Economic Forum 2018 p. 5). We investigated the characteristics and potential of each of the 10 technology headlines, and found that some of the headlines describe several technologies. We studied the technologies in detail and elaborated on the 10 headlines to create a list of 22 technologies that we consider potentially disruptive to the construction sector.

Testing the reframed card concept through interactive exhibitions

To ensure that the *Technology Cards* were applicable in an industrial setting, we launched the cards within a construction consultancy, which we will refer to as company A. The launch event was held in the company innovation room and attracted 15 visitors. Posters, screens, whiteboards and banners in the room encouraged the visitors to try out one of three different games, and if they documented the results of their games, they could participate in a competition. This interactive exhibition of the *Technology Cards* was active for 1.5 month. We also exhibited the cards in another office location. Counting from the number of names in the guest book and the number of participants in the competition, at least 33 people visited one of the innovation rooms and interacted with the *Technology Cards*. Observing further people interacting with the exhibitions without leaving their names, we estimate the actual number of visitors to be much higher.

Designing Tech Sessions

To test the applicability of the *Technology Cards*, we designed a new workshop format called *Tech Sessions*. The purpose of a *Tech Session* was to facilitate that the participants:

- gained an overview of technologies entering construction,
- collectively imagined how the future of the sector will look like,
- prioritised technologies according to their importance (to a specific context), and
- engaged in strategic dialogues aimed at deciding on appropriate action.

The *Tech Session* agenda was designed and refined through several iterations with different game formats. Following the launch event, we held three drop-in *Tech Sessions* that were open for all employees to attend, before settling on a *Tech Session* agenda (see Figure 4). We played game 1 in all *Tech Sessions*. Game 1 invites the participants to prioritise the relevance of the technologies to their (case) company context and sort the cards in two piles accordingly. In about half of the *Tech Sessions*, we used the results from game 1 to play game 2. The optional game 2 asks the participants to create ideas for digitalisation by combining multiple *Technology Cards* and exploring their market potential. In three *Tech Sessions*, we also played game 3, which asks the participants to create a vision for the future (2030) and identify the necessary steps to get there by placing the cards on a timeline ranging from 2020 to 2030.

Figure 17: Participants in a *Tech Session* moving the *Technology Cards* around on a whiteboard

Introduction to the *Technology Cards*

- Brief introduction to all technologies by the facilitator.
- The participants can create extra cards, if they want to add technologies.
- Division of the participants into groups of e.g. 3-4 people

Game 1: Which technologies do we find most important?

- The most important technologies are placed in one end of the board and the least important technologies in the other end.
- The groups are encouraged to write down their thoughts/justifications/ideas next to the *Technology Cards* in either end of the board.

Game 2 (optional): Select a combination of 2-4 technologies that represent an idea for digitalisation

- The groups fill out a template with their initial thoughts on the potential, value and maturity of the idea.

Game 3 (optional): How does the future look like and what should we do to get there?

- The groups create a common vision for the future (e.g. 2030) by selecting and combining cards.

- Backcasting: The groups discuss which (technological) steps that are necessary to reach their common vision. They facilitate the discussion using the cards and a timeline from e.g. 2020-2030.

Presentation of the results and plenary discussion

- Plenary discussion: Did the groups select similar technologies to be important? Where do the groups differ – and why? Which ideas did they come up with?
- Evaluation and discussion of next steps.

Figure 4: A typical *Tech Session* agenda

Validating the Technology Cards through Tech Sessions

The initial *Tech Sessions* created a lot of traction, and we subsequently received requests for *Tech Sessions* from various departments within company A (see Table 3). Surprisingly, not only construction-related stakeholders were inspired by the *Technology Cards*, but also employees and managers working within areas as diverse as environmental impact assessments, soil management, ground pollution and working environment. Having tested the *Tech Session* concept within company A, we updated the design of the *Technology Cards* to version 4. The changes included making the title of the technologies easier to read, and the design element in the top of the cards more intuitive.

In total, we tested the *Technology Cards* and the *Tech Session* concept on 257 participants by means of 17 Tech Session workshops. The participants represented 40 unique organisations, mainly from the construction sector, with other sectors represented, including manufacturing, education, services, and transportation.

Table 3: Detailed list of *Tech Sessions*

ID	*Date*	*Event*	*Card version*	*Participants*	*Number of participants*	*Games*
A	13.06.19	Launch party	3	Open invitation to all employees in company A	15	1,2,3
B	21.06.19	Drop-in *Tech Session*	3		3	1
C	24.06.19	Drop-in *Tech Session*	3		6	1,3
D	26.06.19	Drop-in *Tech Session*	3		3	1
E	03.07.19	*Tech Session*	3	Department managers from environment management departments in company A	7	1
F	06.09.19	*Tech Session*	3	Market managers in construction departments in company A	6	1
G	23.09.19	Strategy course	3	Director and managers in a public facility management organization	5	1
H	11.10.19	*Tech Session*	3	Employees from work environment department in company A	7	1

I	22.10.19	*Tech Session* and workshop	4	The board of directors at a contractor	6	1+2
J	30.10.19	*Tech Session* and workshop	4	Chief executives in a research and technology organisation	9	1+2
K	30.10.19	High Tech Summit 2019	4	Members of an innovation network in a cleantech cluster and conference participants	45	1
L	24.01.20	Lean Design Forum 2020	4	Participants in a construction seminar on Lean Design	20	1+2+3
M	05.03.20	*Tech Session* and workshop	4	Employees from a work environment department at company A	11	1+2
N	25.03.20	Virtual *Tech Session* class	4	Engineering students from the Technical University of Denmark	45	1+2
O	24.03.20	Virtual *Tech Session*	4	Employees from the Centre for Regional Development in a Danish region	40	1+2
P	18.05.20	Open, virtual *Tech Session*	4	Open invitation via LinkedIn. 18 organisations represented.	22	1+2
Q	25.06.20	*Tech Session*	4	Director and department heads at a property management company	7	1
In total		**17 *Tech Session*s with 40 unique organisations represented**			**257 participants**	

The duration of the events varied. A short *Tech Session* to play game 1 lasted approximately 45 minutes, whereas a long *Tech Session* to play game 1 and 2 lasted approximately 3 hours. Often, the *Tech Sessions* were incorporated into a strategy seminar or a digitalisation workshop – to prompt open-minded thoughts about digitalisation. In these instances, the technologies that participants selected as "most important" in game 1 were sometimes used as the point of departure for additional exercises or discussion. Subsequent workshop activities facilitated the strategic dialogue to transition to concrete, actionable plans. When the sessions ended, participants typically held on to a deck of cards, allowing them to read more about each technology and be reminded of the *Tech Session* discussions.

As a result of the coronavirus pandemic, some of the *Tech Sessions* were conducted as virtual workshops. In the virtual *Tech Sessions*, group work was conducted as video meetings with an appointed moderator who shared the screen. The moderator moved pictures of the *Technology Cards* around on a presentation slide to reflect what the group was discussing. Although the groups could not touch and move the physical *Technology Cards* around, the virtual *Tech Sessions* worked surprisingly well. Participants engaged in the group discussion and welcomed the format as an interactive alternative to traditional webinars.

Facilitating the group discussions, both physically and virtually, we found that prioritisation of technologies were highly dependent on the groups' interpretation of the cards. The same card represented different technological applications to different groups, and correspondingly, we will not compare the prioritisation of technologies across *Tech*

Sessions or groups. However, we found that the *Technology Cards* enabled lively future-oriented dialogue among the participants, and we note this as the most important outcome of the sessions. The following section documents the process-related findings from the *Tech Sessions*, focusing in particular on the empirical validation of the theory-frame adopted: design games as ‘instruments of inquiry’.

Findings: *Technology Cards* as tangible instruments of inquiry

As described by Peters et al (2020), the outcome of a card game workshop can be difficult to evaluate without a controlled testing procedure, which often is impractical in real project contexts. Furthermore, it is difficult to distinguish between the cards and the workshop format when evaluating the results (Clatworthy 2011). With this in mind, we evaluated the *Technology Cards* and the *Tech Session* format through observations, interview and feedback from the participants in workshops and *Tech Sessions* with respect to the proposition of cards as tangible ‘instruments of inquiry’.

As described earlier, Dalsgaard (2017) proposes that design tools (so-called instruments of inquiry) possess five qualities: Perception, conception, externalization, knowing-through-action and mediation. Our evaluation of the *Technology Cards* as empirical validation of the propositions suggests that the cards possess four of these five qualities: Framing current challenges (aiding perception), imagining how multiple technologies may affect the future (aiding conception), identifying synergies between technologies (facilitating knowing-through-action), and facilitating constructive dialogue (mediating between the participants). We did not find evidence to neither confirm nor dis-confirm the fifth proposition, proposed by Dalsgaard (2017) concerning externalisation. That is, our findings neither confirm nor dis-confirm that instruments of inquiry in the form of card-based design games support making imagined design solutions part of the real world to allow for evaluation. In what follows, we present empirical evidence for the four qualities perception, conception, knowing-through-action and mediation.

Framing current challenges: aiding perception

When participants prioritised the technologies in game 1, they typically justified their viewpoints by means of examples. These examples often took the point of departure in current challenges experienced by the participants, e.g. *“I think Generative Design is important because it can eliminate tedious design tasks”* or *“I find Virtual Reality (VR) important as it can help us improve our communication with the client”*. In this way, the participants used the *Technology Cards* to identify design challenges – such as tedious design work or suboptimal communication with the client.

Scoping the example case turned out to be important. For example, *Tech Session* P had a group working with hospitals as a case. This group struggled with deciding whether or not a technology was important until they agreed on defining their case as ‘the operation of hospitals’, rather than ‘the construction of hospitals’. Another *Tech Session* (D) hosted construction employees from company A who decided that Construction 3D printing and Construction robots were less important technologies, because they were considered *“relevant to the contractor, not us”*. In this way, the participants did not only prioritise the technological solutions, they also negotiated a common perception of what the case company could and should offer. Referring to Dalsgaard (2017), our findings corroborate that the *Technology Cards* support perception, as the participants used the cards to focus on facets of the (design) situation that could be improved by means of technology.

In few *Tech Sessions* (I and N), the participants did not have a clear idea of their challenges in advance. In these instances, the participants struggled with playing game 2, which entails making an idea concrete and specifying how it will create value for the customer. We found that the 'technology-push' approach of game 2 was difficult when the participants did not have in-depth knowledge of the problem domain. We would therefore suggest that game 2 is supplemented with a 'market-pull approach' that explores the problem domain, e.g. by means of a SWOT analysis or Porter's five forces (Meyer et al. 2008).

Imagining how multiple technologies may affect the future: aiding conception

We observed that the images and concrete use cases depicted on the cards helped the participants in gaining a quick understanding of the (often abstract) technology. Several participants commented that they liked the straightforward format of the cards, e.g.

> "Of course we could have used a lot more time on this, but that was not the task here. We tried the cards and I actually think they worked very well as an object for discussion on what is possible" (Participant in *Tech Session* P, group 3. [Translated])

When prioritising the technologies, some groups started with going through the whole deck of cards in sequence, whereas other groups let participants take turn in selecting an interesting technology and arguing for its importance. This difference in approach turned out to have a great influence on the flow of the discussion. Groups that went through the card deck from one end to the other ended up with an evaluative mind-set which facilitated discussions of whether or not a technology was relevant. In contrast, the groups that let the discussion be driven by curiosity obtained a design thinking mind-set that facilitated creative discussions of how the technologies might be applied.

In one case, the evaluative approach entailed that one of the group members (a domain specialist) took up a role where he possessed the "correct" answer about where a technology should be placed on the board. This was path-setting and at the time deemed unfortunate, considering that the *Tech Session* was intended to facilitate exploratory discussions about an uncertain future. In contrast, the curiosity-driven approach ensured that all the group members were given speaking time and kept an open-minded attitude which facilitated creativity.

We observed that the concrete use cases depicted on the cards did not refrain participants from thinking about other, related use cases. For example, participants used the *Drone survey* card to describe other drone-related activities, such as transportation or mapping by drones. As intended, the *Technology Cards* were used as a point of reference in the discussion – and during the *Tech Sessions*, the specific contextual meaning of each card was negotiated between the participants. Take for example the *Augmented reality* (AR) card. One group used this card to talk about how public hearing procedures could change if citizens experienced the planned construction project in AR. Another group used the same card to discuss how design consultants could use AR to compare design drawings to what was actually built on site. This emphasises that both groups considered this technology very important, but for different reasons. Concluding by referring to

Dalsgaard (2017), we find that the *Technology Cards* do aid conception, as they help people to examine and get an overview of different technologies that could improve their current situation.

Identifying synergies between technologies: facilitating knowing-through-action

In most of the *Tech Sessions*, we noticed that the participants – unprompted – began clustering technologies that they considered related or interdependent. During discussion on how to prioritise the technologies, the participants would identify relationship between different *Technology Cards* and group them on the board. For example, one group clustered *Reality capture* and *Drone survey*, as both of these technologies were considered useful for mapping as-built structures. This group also clustered *VR, AR* and *Building Information Modelling (BIM)*, arguing that BIM is a prerequisite for implementing AR and VR. In this way, the *Technology Cards* facilitated discussions on the synergies between different technologies:

> "We quickly identified a number of cards that were very relevant. Finding something that was less relevant was more difficult. And then we discovered the synergies that emerged." (Participant in *Tech Session* P, group 4. [Translated])

Typically, the clustering of technologies happened as an unintended side effect of the discussion, and the participants seemed delighted to have identified the relationships. Drawing on Dalsgaard (2017), we consider these incidences as instances of knowing-through-action.

Facilitating constructive dialogue: mediating between the participants

In some of the *Tech Sessions* (e.g. D, H, O), the participants had very similar fields of knowledge, working as colleagues in the same organisation. In these sessions, the discussions of technological possibilities were concrete and actionable, and typically took actual challenges experienced by the participants as points of departure. In other *Tech Sessions* (e.g., K, L, N, P), the participants represented different domains and/or different organisations. In these sessions, we found that the participants were curious to learn and gain inspiration from each other. Whether or not the participants possessed detailed knowledge about the technologies, or the case company, turned out to be less important than we had expected. For example, one of the participants who came from a publicly-owned environmental data organisation, joined a group that worked with an e-mobility company as a case. He stated:

> "I think the cards worked surprisingly well, [because] we quickly began discussing some relevant things. I knew nothing about e-mobility before, but now I know a bit more." (Participant in *Tech Session* P, group 1. [Translated])

Several participants suggested that we created new editions of *Technology Cards* that target other sectors, such as the environmental sector or healthcare. Such feedback suggests that the *Technology Cards* are applicable and inspiring to participants from other sectors than construction. Despite the initial focus on business contexts, we also see a potential for applying the Technology Cards in other contexts such as in municipalities or hospitals.

We found that the game-like format of the *Technology Cards* encouraged the group members to take turns in joining the discussion, as is typical when playing traditional card games for the purpose of entertainment. We observed that the rather simple game rules facilitated that the discussions quickly centred around relevant aspects of the future:

> "I think that the *Technology Cards* are great for illustrating how you easily - within a short timeframe - can boil down what is important to focus on in your company" (Participant in *Tech Session* K. [Translated])

This observation suggests that the *Technology Cards* lowered the entry barrier for participants joining technology-related discussions about the future. In this way, our findings confirm that the *Technology Cards* as tangible instruments of inquiry worked well also as a mediation tool and facilitated cross-disciplinary dialogue between the participants (Dalsgaard 2017).

Discussion

Research presented in this paper with a focal point on the *Technology Cards* demonstrates contributions to knowledge in three ways: 1) by providing a way to explore how multiple technologies in combination will affect the future, 2) by offering an inclusive approach to involve stakeholders from different backgrounds in discussions on digital futures, and 3) by demonstrating synergies between the fields of design and futures studies. We also reflect on the versatility and limitations of the *Technology Cards*, and provide pointers to areas for further work.

Contributing to knowledge on how design games aid futures studies

A combinatorial view on the implications of multiple technologies

Discussing the future is important. However, discussions about digital futures tend to centre on what specific technologies can and cannot do. What is blockchain really? What defines a smart city? How humanoid have robots become? Although these types of questions are relevant, they also tend to derail discussions about the future. Instead of discussing what we want the future to be, we end up discussing what is technologically possible. This is unfortunate, as the future should not only be shaped by technological options but also by a number of other factors, such as societal concerns and desires for the future.

At first glance, it may seem that the *Technology Cards* are just another artefact that focuses solely on technological potential and disregards other aspects of the future. Having said this, we do, however, propose the opposite. The *Technology Cards* describe each technology with a few sentences to provide a basic understanding of each term without going into detail with the specific potential of each technology. This format empowers users to get an *overview of multiple technologies*, enhances their attention to *synergies between technologies* and allows for people to contribute to dialogue on the future by *bringing in other concerns at an equal standpoint to that of technologies*. Keeping in mind that digital technologies have a transformative potential for changing entire sectors of society, we propose that such a holistic, combinatorial view of technological potential is needed.

An inclusive approach to discussing the future

In our experience, discussions about technologies can easily become 'nerdy'. This may, for example, include discussing the difference between supervised and non-supervised machine learning, or debating whether mixed reality is a better descriptor than augmented reality and virtual reality. While these are important issues, the ‘nerdiness’ of the discussion tends to exclude non-technology-savvy people. This is unfortunate as it leaves technology experts to discuss and define our ‘preferred’ future.

As exemplified in the findings section, one of the strengths of the *Technology Cards* design game is its ability to create a setting that inspires stakeholders from multiple backgrounds to participate. The game-like characteristics of the *Technology Cards* encourages people to play around with the cards, experiment with different combinations and envision different possible futures. As the game-like format of the *Technology Cards* is typical for design games, this paper demonstrates the relevance of *using design games to make dialogues on the future more accessible and democratic,* by involving multiple stakeholders from various backgrounds.

Connecting futures studies and design

The development of the *Technology Cards* demonstrates how research from the fields of future studies and design connect and overlap. Futures studies excel in identifying trends and outlining multiple possible futures and the field of design excels in turning abstract problems into tangible solutions, while taking the needs and wants of stakeholders into account. The *Technology Cards* bridge these two research fields, as they *facilitate participatory, long term-oriented design thinking activities*. We see a great potential for further research connecting these two fields of study to explore the implications of digitalisation.

Reflections on applicability and versatility of the *Technology Cards*

Like any other design tool, the *Technology Card* deck is well-suited for certain situations and less (or not) suitable in others. In the following, we reflect on limitations of the *Technology Cards* and the *Tech Session* concept, as these are central to understanding applicability and versatility of the design game as a tool (Dalsgaard 2017).

Technologies and trends shaping the future

As the name implies, the *Technology Cards* focus on technology. However, the future of the construction sector is not only affected by technological possibilities but also by major trends such as sustainability and urbanisation. Technologies and trends are closely related terms. Whereas technologies create new ways of doing business, trends describe changes to the business environment. Trends can be clustered into five overarching themes using the STEEP framework: Social, Technological, Economical, Environmental, and Political (Szigeti et al. 2011). The *Technology Cards* can be used to understand technological trends. However, other themes are equally important as they impact the sector, e.g. by affecting legislation and changing the client’s preferences. People using the *Technology Cards* may therefore find it useful to supplement the games with another game (e.g. the Drivers of Change Cards, see Table 2), which present important trends in detail. Alternatively, users could design a new workshop format or game that uses the *Technology Cards* to explore certain trends in detail. We took the initial steps in this direction in *Tech Session* L, where we asked the participants to identify how technologies could transform construction practices towards sustainability in 2030. This *Tech Session* was framed using sustainability challenges of construction and a concluding discussion on the role of technologies as means towards sustainable futures.

Technology-push and market-pull approaches

The *Technology Cards* encourage a technology push approach. This kind of approach provides a good overview of the range of technological possibilities; the solution space. A ‘technology push approach’ is therefore well-suited for exploring potential futures, and anticipating future market demands. However, a technology push approach also entails a risk of letting the ‘gadget factor’ drive development of new products and services (De Roeck et al. 2014). In other words, participants may be tempted to say “VR sounds interesting, let’s do that” without having a clear picture of the ‘fit’ with market conditions or business applications. To avoid this, users may benefit from supplementing the *Technology Cards* with a ‘market pull approach’ that identifies the needs in the problem space (e.g., a SWOT analysis or a customer journey). Ensuring the right match between problem and solution is an essential activity in design (Dorst and Cross 2001). By combining technology-push and market-pull, users can ensure that their technological design initiatives rest on a solid market- and business understanding. We also see a promising potential for developing ‘business model cards’ that can be combined with the *Technology Cards* to facilitate the development of digital solutions.

Implementation of new technologies

Successful implementation of technology is a complex undertaking. It depends on a number of factors such as business models, customer segments, funding options, or collaboration possibilities. Timing is also critical. While the potential of a new technology may sound promising, the technology may need to mature before it is applicable in a specific business application. While the *Technology Cards* are suitable for identifying and selecting technologies to invest in, we suggest that users consult other tools for their actual implementation.

Outlook and further work

Imagining how digital technologies will affect the future is difficult. Nevertheless, imaginative narratives of the future are important, as they (deliberately or not) affect present-day strategic choices (Ernstsen et al. 2021). For example, a construction company that focuses on environmental sustainability may choose to invest in internet of things-related technologies that improve energy consumption of the built environment. In contrast, a construction company that believes in a future of fully automated design and construction processes may choose to invest in technologies that support this vision, i.e. generative design technology or robotics. These differences in strategic choices will not only affect the competitive position of the company, they will also actively contribute to shaping the future of the sector.

Digitalisation will have an enormous impact on society in the years to come, and, correspondingly, there is large potential for further research on the topic. Design involves creating socio-technical solutions that satisfy complex networks of stakeholders. As such, we believe that design researchers and design practitioners are particularly well-equipped to investigate future implications of digitalisation. Further research might explore how digitalisation can help leverage societal aims such as those explicated by the Sustainable Development Goals. Further research might also investigate how design methods can contribute to discussing and designing digital futures.

Conclusion

Digital technologies such as artificial intelligence, big data, virtual reality, robots and internet of things will have a massive impact on the future. But what kind of change will they create? And how will that affect businesses?

In this paper, we have introduced the *Technology Cards* – a design game that engages users in discussing the impact of multiple digital technologies on their own business context. We developed and tested the *Technology Cards* in 17 *Tech Sessions* with 257 participants from 40 organisations. By framing the cards as instruments of inquiry, we found that they aid users in a) framing current challenges, b) imagining how multiple technologies may affect the future, c) identifying synergies between technologies, and d) facilitating constructive dialogue. We demonstrated the synergistic potential of combining the fields of design and futures studies to explore the cross-disciplinary impact of digitalisation. Although the *Technology Cards* were designed specifically for businesses in the construction sector, we found that the cards were also relevant to stakeholders from other sectors. Considering the game-changing impact of digitalisation on entire sectors of society, we argued for the importance of including both technology-savvy and non-technology-savvy stakeholders in discussions on the future. By introducing the *Technology Cards*, we presented a dialogue-based design game that highlights the implications of multiple technologies on the future of business and aids business managers in navigating in a digital future.

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Appendix E: The *Technology Cards*

TECHNOLOGY CARDS

The Technology Cards present 22 digital technologies that may create disruptive changes in the construction sector.

Use the cards as
- **an information tool** to get an overview of digital technologies entering construction
- **a dialogue tool** to imagine how the future of the sector will look like
- **a strategic tool** to prioritise technologies according to their perceived importance

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PREFABRICATION AND MODULAR CONSTRUCTION

Construction elements and modules are produced off-site in factory-like settings, transported to site and assembled there. The prefabricated units may be, e.g., small elements in a façade or entire factory-fitted bathrooms.

+ Faster construction process on-site
+ Less material waste
+ Less dependency on weather

- The design can be somewhat constrained by the standardised size of modules

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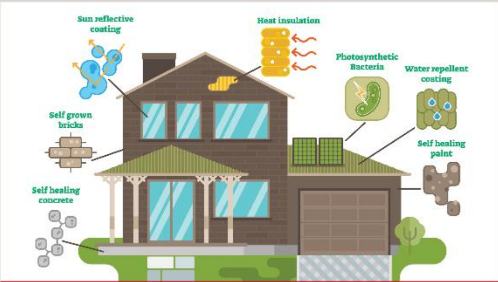

NEW BUILDING MATERIALS

New building materials, such as translucent wood, self-healing concrete, light-emitting concrete and air-purifying bricks, can reduce material usage, decrease the energy consumption of the built environment and/or improve the indoor climate in buildings.

+ Reduced need for maintenance because of improved material lifetime
+ Potentially improved user experience of the built environment

- Research and regulatory approval required

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CONSTRUCTION 3D PRINTING

Using a 3D printer to print construction structures layer by layer. To demonstrate the technology, researchers and entrepreneurs have printed bridges in metal, concrete or polymer off-site, and entire buildings in concrete or clay on-site.

+ Faster construction involving fewer workers
+ Possibility of new designs with complex surfaces

- Research and regulatory approval required

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DRONE SURVEY

Drones are unmanned flying vehicles that are typically remotely operated. By attaching sensors to a drone, it can be used for mapping terrains, making virtual models of built structures, inspecting maintenance needs or monitoring the progress of a construction project.

+ Cheap identification of construction requirements
+ Easy mapping of progress over time
+ Improved safety because of remote operation
- Optimal weather conditions and drone license necessary

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AUTONOMOUS CONSTRUCTION VEHICLES

Autonomous dozers, excavators, load-carriers and haul trucks can be used for excavating and grading soil on construction sites. Small rovers carrying tools and materials can follow workers around. The vehicles are often connected to allow for co-ordinated actions.

+ Improved productivity, as one operator can supervise several vehicles
+ Enhanced safety of operators

- Precision work can be challenging for the autonomous vehicles

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CONSTRUCTION ROBOTS

Machines that can be programmed to undertake complex construction-related tasks and operate either autonomously or semi-autonomously. Construction robots may be used for, e.g., laying bricks, welding steel, tying rebar or creating formwork.

+ Faster construction on-site
+ Increased labour productivity
+ Improved safety for human workers

- Limited ability to perform more than one type of task

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INDUSTRIAL EXOSKELETON

Wearable devices that can support a construction worker in his movements and amplify his strength when lifting heavyweight items or tools on-site. Passive exoskeletons function by shifting pressure from, e.g., arms and shoulders to the body core or legs.

+ Empower workers to perform heavy lifting
+ Enhance safety as a result of fewer injuries
+ Improve efficiency as a result of less strain on workers

- Can create discomfort if worn for too long

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VIRTUAL REALITY (VR)

A simulated computer-generated environment in which a user can immerse himself by means of virtual reality (VR) glasses and handheld controllers. During construction design, VR can allow users to experience walking around inside a not-yet-constructed building.

+ Better designs because of user involvement
+ Enhanced collaboration between construction stakeholders

- Restricted communication as the VR user is isolated from the real world

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AUGMENTED REALITY (AR)

By means of augmented reality (AR) glasses, a smartphone or a tablet, an AR user is able to see a visual overlay of computergenerated information on top of the real world. On construction sites, AR may be used to visualise hidden structures or to compare the design model to what is actually built.

+ Improved on-site planning and communication during construction
+ Better designs as changes are visualised

- Risk of accidents as operators can be distracted by the virtual overlay on reality

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BIG DATA ANALYTICS

Analysing a large volume of diverse data to reveal patterns. In construction, big data from previous projects can be used to improve project planning, and big data from facility management systems can be used to optimise the operation of the built environment.

+ Improved quality, time and cost of construction projects
+ Better operation of the built environment

- Challenging to leverage data from multiple sources in a meaningful way

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ARTIFICIAL INTELLIGENCE (AI) PREDICTIONS

Artificial intelligence (AI) algorithms enable computers to predict certain outcomes based on large amounts of data. In construction, AI may be used to predict the risk of project cost overruns, the risk of on-site accidents or the need for maintenance over time.

+ Improved project quality, as decisions are based on data
+ Optimised utilisation of assets

- Challenging to collect sufficient, quality data to train the AI

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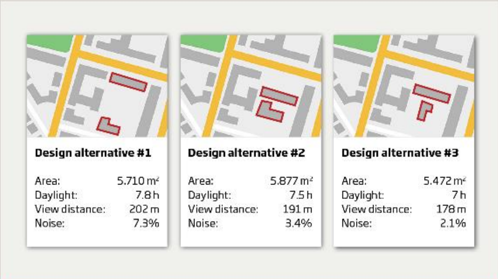

GENERATIVE DESIGN

A computer-aided design process generating hundreds of possible designs based on input parameters and constraints defined by the designer. The designer may subsequently vary the parameters to optimise and select the best solution.

+ Improved final designs as alternatives have been explored
+ Easier to accommodate change requests

- More time spent on initial design and the defining of parameters

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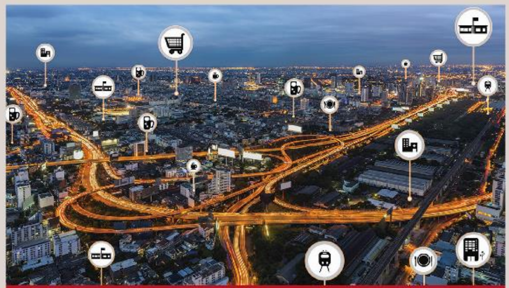

SMART CITIES

Sensors installed in the built environment provide smart cities with knowledge on how users experience and interact with the city. This can be used for managing traffic flows, optimising the use of utility networks, identifying high-risk crime areas, engaging users in city governance and more.

+ Better designs of urban areas, as they are informed by knowledge of user behaviour
+ Improved utilisation of the built environment

- Need for prevention of cyber threats and protection of privacy rights

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INTELLIGENT BUILDINGS

Intelligent buildings strive to create an optimal indoor climate for their occupants and optimise the use of assets and energy. Each building uses data from, e.g., facility management systems, weather forecasts and sensors measuring, e.g., occupancy and air quality in the building.

+ Improved user experience of the building
+ Improved asset utilisation
+ Optimised use of resources as a result of, e.g., predictive maintenance

- Challenging to combine data sources

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SMART CONSTRUCTION SITE

Sensors and cameras are installed on site or worn by construction workers. This allows project managers to monitor project progress and optimise working efficiency. Moreover, the detection of workers' exposure to high noise or repetitive motions can help to increase safety on-site.

+ Optimised utilisation of construction tools
+ Improved safety on-site
+ Better construction quality from monitoring of, e.g., curing processes

- Need for protection of privacy rights

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CLOUD-BASED CONSTRUCTION MANAGEMENT

When project information is stored in the cloud, it is immediately accessible to all project stakeholders regardless of location. Rather than relying on paper print-outs, on-site workers can access the most recent project plan by means of mobile devices.

+ Enhanced project management
+ Better project results because of better version control

- Data sharing between different clouds is difficult because of proprietary formats

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BLOCKCHAIN

Blockchain technology provides a secure method of storing and transferring data. Blockchain-based 'smart contracts' can ensure that money is transferred between stakeholders, when certain pre-defined criteria have been obtained. This make approval processes transparent and legally binding.

+ Fewer disputes from unclear contracts
+ Improved traceability in workflow
+ Reduced transaction costs

- Need for pre-defining criteria and standardising processes

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REALITY CAPTURE

Creating realistic, virtual representations of buildings or sites by means of laser point clouds (LiDAR technology) and/or photos from multiple angles (photogrammetry). Reality capture models may also be geotagged, building information modelling (BIM) compatible and photorealistic.

+ Reduced time and cost of capturing on-site conditions
+ Improved accuracy of 3D models
+ Eased communication between stakeholders

- Need for large data processing capability

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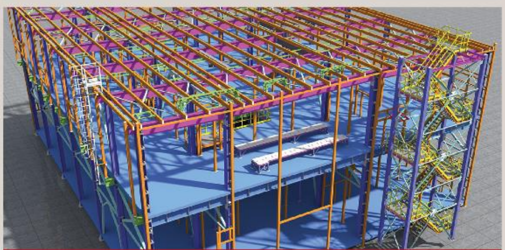

BUILDING INFORMATION MODELLING (BIM)

A BIM model is a virtual 3D model of a construction project. Building information modelling refers to the collaborative, cross-disciplinary process of designing, qualifying and realising such a model. It can aid in the early detection of potential issues and provide documentation of the finished project.

+ Improved speed of delivery
+ Better design quality, as 3D visualisations are easy to comprehend

- Challenging implementation involving many different stakeholders

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4D, 5D AND 6D BIM

4D BIM adds time-related information to 3D BIM models to enable detailed scheduling of the construction process. 5D BIM adds costs to BIM components to assist in the calculation of total project costs. 6D BIM adds lifecycle properties to enable optimised asset management.

+ Better planning and faster construction
+ Enhanced ability to estimate the consequences of change requests

- Challenging to ensure that all modelled data are correct and up-to-date

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AGENT-BASED MODELLING AND DISCRETE EVENT SIMULATION

Simulations may be used to visualise how multiple humans will act and interact while they evacuate a building or travel through a congested area. Moreover, simulations can be used to identify bottlenecks in a supply chain and, e.g., optimise the use of trucks on construction sites.

+ Better designs, as issues can be detected from an early stage
+ Enhanced visual communication
+ Optimised use of assets during construction

- Difficult to validate simulations

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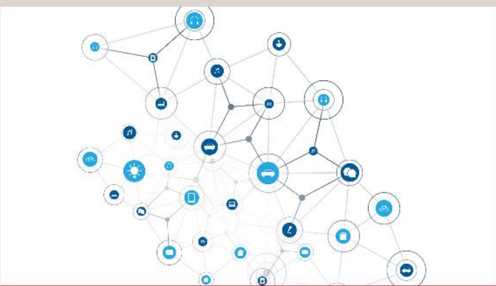

LINKED DATA

A method of structuring data to clarify their relationship. By linking data from a Building Information Model, a computer is able to answer questions such as 'How will 10% larger windows affect the cooling need?' and calculate the consequences of any design changes

+ Easier to accommodate change requests
+ Faster construction process as a result of more streamlined work processes

- Need for strict access control and security protocols to avoid data breaches

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Mark which phase(s) this technology will affect:

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Drawing:

Technology name:

Short description:

Pros and cons:

Your name:

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Mark which phase(s) this technology will affect:
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Drawing:

Technology name:

Short description:

Pros and cons:

Your name:

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TECH SESSION

In a Tech Session, the participants play with the Technology Cards and engage in strategic dialogues. Various games may be played depending on the purpose of the session.

Agenda example

Game 1: Which technologies do we find the most important?
- Sort the 22 Technology Cards into two categories according to importance.
- Presentation of results and plenary discussion.

Game 2: How does the future look like and how do we get there?

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