THE BARRIERS TO 3-d CONSTRUCTION PRINTING A CEMENTITIOUS OUTER WALL

1 Title page with personal data

Thesis, P5 Report
The barriers to 3-d construction printing a cementitious outer wall

"What are the barriers to 3-d construction printing a cementitious outer wall in the construction industry?"

Personal data
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2 Foreword

2.1 The motivation for choosing this research subject

This research was motivated by a desire to contribute to the discourse and encourage the use of evolving technology in solving fundamental social, socio-economic and environmental issues both on a national scale in the Netherlands and on a global scale. As such, this thesis topic combines multiple interests, including my interest in real estate, property development and construction, robotics and entrepreneurship.

The thesis focuses on off-site manufacturing for the sustainable as economically interesting design and construction of residential properties, exploring the use of 3-d construction printing in the construction industry. This domain is also called, digital manufacturing. It is a perfect vehicle to develop my interest in the usability and the market potential of innovative products and builds on my previous projects, which include the design of a water-saving product and development of a commercial satellite data platform. I am aware that in my earlier projects, the ideas have failed - mainly due to my lack of research abilities concerning product-related research. I believe that my interest in construction materials and sustainable development stems from my technical grounding in an undergraduate degree in architecture. This research was therefore in part motivated by these interests and my third passion, robotics. I intended to use this thesis to develop my understanding of robots in construction, particularly 3-d construction printing techniques. This thesis was therefore partially motivated by a desire to expand the feasibility and scalability of standardised forms of construction - particularly in residential property construction.

2.2 The vision of the research subject

The vision that I had for this research project was to enhance and expand my knowledge in 3-d construction printing as well as the overall understanding that I had on the interface between engineering designs, technology, and the development of a sustainable built environment. My desire was to learn more on 3-d construction printing because it is a layered construction technology that uses 3-d printing to help fabricate large constructions or building components. I also believe that the technology provides a remarkable opportunity for automating construction processes thereby creating room for the attainment of sustainability in the construction industry as well as bridging the gap in the demand and supply of residential properties. I was also hoping to understand the view of the construction industry about existing barriers as well as practical application of 3-d construction printing in the built environment. I wanted to evaluate the level of interest that the construction industry has on technology use in construction projects and techniques of overcoming existing barriers. Moreover, there are potential new materials, there are barriers and I have researched the way how barriers can be discovered and potentially be overcome in the domain of digital fabrication with the focus on cementitious 3-d construction printing.

2.3 Profile for the future role in the construction industry

I have experience working in different organizations and given my educational background; my intention is to use this research study to take my career to the next level in as far as economical and sustainable design and construction in the domain of digital fabrication. I believe that this project can help me attain my goals and improve my overall ability to contribute significantly towards sustainable project delivery at the organizational level.

2.4 Study targets for the research project: general and personal

My study targets were to develop the research in a staged manner, completing the thesis within the agreed timescale. My personal objective was to develop my report writing ability and my knowledge of 3-d construction printing while keeping the focus on the managerial dimension and processes of the built environment. I intend to pursue an (entrepreneurial) career path in real estate development or possibly in digital manufacturing depending on the offers that will be around. This research offered the opportunity to continue this process the combination of real estate and digital manufacturing in an informed manner. I wanted to use this thesis as a vehicle to improve my ability to focus on a specific research question and my investigative abilities.

2.5 Study targets for the research project

My target for this study was to ensure that the research well-staged and completed within the agreed timescale. Personally, I wanted to improve my report writing ability and general knowledge in 3-d construction printing while focusing on managerial dimension as well as processes of the built environment. This is especially critical because my passion is to develop as an entrepreneur in the development of real estate. With this research, I can pursue this career path in a well-organized and informed manner. I want to utilize this thesis as a vehicle that can help me improve my ability to redirect attention at a given research question and apply particular investigative capabilities and skills.

The core objective of this thesis is to gain more understanding of the built environment and more precisely, the sector of digital fabrication focused on 3-d construction printing. Hence, the goal of this study is to carry out a comprehensive and detailed literature review, exploring different sources that discuss 3-d construction printing. I will also go through the attitudes and perceptions of experts with real-world 3-d construction experience on 3-d construction printing itself and its practicality in the Netherlands. Moreover, my wish was to come up with a robust methodology that features clear and coherent research framework to provide a platform for progressing with this study and consequently conduct an interview and questionnaire survey. After data gathering, analysis was conducted and discussed to aid the formulation of conclusions basing on findings.

2.6 Personal learning objectives

My learning objectives for this research are as follows:

- To improve my written communication skills.
- To enhance my investigative and analytical skills.
- To develop my ability to utilize effective research skills.
- To utilize this research to bolster the knowledge that I have about sustainable development.
- To improve the knowledge that I have on 3-d construction printing and at the same time focusing on managerial process and dimension of the built environment.
- To take my report writing skills and ability to the next level.

3 Samenvatting

3.1 Abstract

Verschillende technologieën op het gebied van digitale fabricage zijn geïntroduceerd in de bouwsector om efficiëntie te bevorderen. Deze thesis biedt een platform voor het beoordelen van 3-d constructieprinttechnologie. Deze thesis onderzocht de barrières die het gebruik van 3-d printtechnologie in de bouwsector bemoeilijken. De betekenis of effecten van deze barrières zullen worden geëvalueerd door de posities en standpunten van de studiedeelnemers te beoordelen. Deze barrières omvatten:

- Hoge kosten van de printer.
- Onvolwassenheid van print partners.
- Onduidelijke gevolgen met betrekking tot regelgeving.
- Onmogelijkheid om grotere structuren te maken.
- Hoge kosten van gedrukte structuren.
- Gebrek aan commerciële levensvatbaarheid.
- Gebrek aan klantenondersteuning.
- Gebrek aan voldoende succesvolle voorbeelden.
- Onvoorbereide architect / ontwerper.
- Moeilijkheden om printers te vervoeren.
- Technologieonderbrekingsrisico.
- Behoefte aan dure speciaal materieel

De drie gesignaleerde problemen klimaatverandering, uitputting van natuurlijke hulpbronnen en sociaal-economische factoren worden allemaal als belangrijk beschouwd, die vrij breed is als ze niet worden uitgelegd met een goed uitgangspunt. Het uitgangspunt van deze thesis is echter dat het gaat over het bijdragen aan het oplossen van deze 3 grote problemen (nationale en zelfs wereldproblemen). Daarmee is de schaalbaarheid van een product en de massale haalbaarheid van 3-d printen van cruciaal belang voor wereldwijde acceptatie en het oplossen van deze wezelijke problemen in plaats van alleen maar een nichemarkt te creëren voor vrije-vormarchitectuur. Wanneer een product zeer schaalbaar is en echt waarde oplevert, kunnen veronderstelde grote particuliere (en zelfs publieke) investeringen worden aangetrokken als het product vanuit het

oogpunt van de belegger logisch is. Daarom moet 3-d constructieprinten echt waarde toevoegen op een grotere schaal en niet alleen voor een nichemarkt op de langere termijn. Het moet duidelijk zijn om te zien of grote investeringen waard zijn voor 3-d constructieprinten. Bovendien wilde ik leren hoe ik een nieuw product voor mezelf kon onderzoeken en wat het potentieel is om een oplossing te bieden voor belangrijke (wereld) problemen. Kortom, er zijn potentiële nieuwe materialen, er zijn barrières en ik onderzoek hoe barrières kunnen worden ontdekt en mogelijk worden overwonnen in het domein van digitale fabricage, met de nadruk op cementgebonden 3-d constructie geprinte buitenwanden.

Deze thesis is in verschillende delen verdeeld. De eerste sectie was de introductie van waar het onderwerp is geïntroduceerd. Het volgende deel behandelde de onderzoeksmethoden en, nog belangrijker, de technieken die werden gebruikt om gegevens en informatie van de onderzoeksparticipanten te verzamelen. Van daaruit werden de belangrijkste onderzoeksresultaten verstrekt. Hier werden de resultaten verdeeld in interviewresultaten en vragenlijstresultaten. Vervolgens werd er een korte conclusie gegeven met een samenvatting van de belangrijkste delen van het artikel, gevolgd door mogelijke aanbevelingen.

3.2 Trefwoorden

Digitale fabricage, 3D-constructieprinten, FLAM, Robotica, Algoritmen

3.3 Introductie

Technologische innovatie is de basis geweest voor effectiviteit en succes in veel industrieën. Het probleem van de adoptie is echter altijd al een punt van zorg geweest vanwege mogelijke barrières die de implementatie belemmeren. 3-d printen is een opkomende technologie die nog niet volledig is geaccepteerd in de bouwsector. Voor de goede orde: mits goed toegepast, de technologie is veel beter dan de conventionele constructiemethode omdat deze kosteneffectief en efficiënt is gebleken. Daarom richt dit onderzoek zich op het bepalen van mogelijke redenen die de toepassing van de technologie in de bouwsector in het algemeen moeilijk maken. Het onderzoek gaat over de mogelijke barrières die zijn genoemd in andere onderzoeken of door andere deskundigen in de bouwsector en gebruiken vragenlijsten en interviews om te bepalen of de belemmeringen significant zijn of niet. Van daaruit kunnen een korte conclusie en mogelijke aanbevelingen voor de toekomst worden gegeven.

3.4 Onderzoeksmethoden

De onderzoeksmethoden die in dit onderzoek werden gebruikt, waren onder meer het gebruik van vragenlijsten en interviews. Interviews met een duur van 50 minuten werden uitgevoerd waarbij 9 experts werden geïnterviewd. Het telefoontje werd opgenomen en later getranscribeerd in een Word-document om het begrip van de inhoud van het gesprek te vergroten. Vragenlijsten werden echter ontwikkeld en verspreid onder verschillende onderzoeksparticipanten. De vragenlijst draait om 12 belangrijke gebieden die vermoedelijk mogelijke hindernissen zijn voor de acceptatie van 3-d printtechnologie in de bouwsector. Ondertussen werden alle studiedeelnemers, inclusief de mensen die werden geïnterviewd en degenen die op de vragenlijsten reageerden, herinnerd aan de ethische waarden van het onderzoek. Ze werden er bijvoorbeeld allemaal aan herinnerd dat hun privacy wordt beschermd. Ook kregen de deelnemers te horen dat ze vrijwillig aan de studie kunnen deelnemen en als ze willen stoppen, moeten ze niet aarzelen om dit te doen als dat hen comfortabel zal maken.

3.5 Belangrijkste onderzoeksresultaten

3.5.1 Interviewresultaten

Gespreksresultaten van de deelnemers gaven meer inzicht in de ernst van het probleem van 3-d printen en de toepassing ervan in de bouwsector. Terwijl er werd geprobeerd uit te vinden hoe FLAM (Fungal-like Adhesive Material) met succes kan worden geïntegreerd in een 3-d geprinte cementachtige buitenmuur, evenals dingen die te maken hebben met isolatie-effecten en de kosten van een dergelijke benadering, toonden de interviewresultaten aan dat aandacht wordt besteed bij het printen van beton en dat FLAM een nieuw materiaal is dat mogelijk kan worden toegevoegd aan de buitenmuur of als additief in het cementachtige materiaal. De werkelijke kosten die worden gemaakt met het gebruik van FLAM zijn de kosten die zijn verbonden aan het vervangen van zand of andere materialen. FLAM is een soort buffer en dat verhoogt de isolatiewaarde omdat het dezelfde structurele eigenschappen of functies heeft als materialen die op hout lijken (Sanandiya, 2018). In Nederland betekent dit echter dat het wandelement waarschijnlijk uit een enorme dikke wand moet bestaan. Het wordt verondersteld dat FLAM kan worden gebruikt als conventionele isolatie die men nodig heeft voor materialen zoals bio-parels. Het materiaal heeft een significant effect op de printbaarheid van een materiaal in verhouding tot de waarschijnlijkheid omdat men moet eindigen met een printbaar materiaal. In de resultaten van het interview zagen de geïnterviewden FLAM-materiaal als duurzaam en een geweldige manier die mensen in de bouwsector kunnen gebruiken om de CO2-uitstoot te helpen verminderen. Een deel van de informatie die gedeeld werd met de geïnterviewden was dat de kosten van FLAM lager zijn dan 2 $ / kg, vergelijkbaar met standaardkunststoffen en 10 keer lager is dan de prijs van gewone filamenten voor 3-d printen. Dit materiaal kan ook worden gebruikt om grote structuren te 3-d printen voor objecten zoals een buitenmuur (Fernandez, 2019). Dus, volgens de geïnterviewden, is het mogelijk om een passieve structuur te creëren dat zeer goed geoptimaliseerd is om de isolatiemogelijkheden volgens de toepasbaarheid van de applicatie parametrisch te modeleren. Hetzelfde gebouw, dezelfde buitenmuur kan op maat worden gemaakt voor de specifieke klimaatconditiezone per zone, klimaat voor klimaat. Het cementachtige materiaal is lange tijd iets wat vrij ver weg geweest, bijvoorbeeld van machines. Ingenieurs praatten vroeger over beton en praatten niet over de grondstoffen erachter. Er zijn veel entiteiten die waarschijnlijk geïntrigeerd zijn om de realisatie van materialen voor recycling van buitenmuren en het tweedehands materiaal te promoten, wat tot de verbetering van 3-d printen ongehoorde mogelijkheden was.

Terugkijkend naar de schaalbaarheid van dit materiaal, is er potentieel om dit product op te schalen. Geen van de geïnterviewden hoorde echter al eerder over FLAM-materiaal en ze wisten nog niet hoe dit in de echte wereld zou werken. Dit is geen verrassing, want het onderzoek is eind 2018 gepubliceerd. Eén geïnterviewde had echter wel waardevolle kennis van andere biologisch afbreekbare en ecologisch duurzame materialen. Volgens een interviewer PETG (+ - $ 18, - / kg), zijn PVDF (+ - $ 18, - / kg) en ASA (+ - $ 4,5 / kg) potentiële op polymeren gebaseerde 3-d print bouwmaterialen. Deze materialen zijn fijner om mee te printen dan cementachtige materialen, hebben betere ontwerpmogelijkheden dan conventionele materialen, zijn duurzaam en 3-d geprinte huizen zijn een mogelijkheid. 3-d printen van hoogbouw, die een hogere dichtheid heeft dan familiehuizen, is momenteel echter niet mogelijk met polymeren en daarom is het momenteel veel minder schaalbaar dan cementachtige materialen. Bovendien kan worden geconcludeerd dat er een praktische kenniskloof bestaat tussen FLAM (en andere materialen op basis van polymeren), dat de articulatie van concurrentiesterkte nog niet grondig is overwogen en er een gebrek aan standaardisatie van FLAM bestaat. Daarom is het duidelijk dat deze factoren een belemmering vormen voor de schaalbaarheid van FLAM (Coutu, 2014; Nielsen et al., 2018).

De resultaten van het interview vormden ook een basis voor het verkennen van de innovatieve capaciteiten van 3-d printen met betrekking tot de functie en het ontwerp van een cementachtige muur. Volgens hen kunnen mensen in de bouwsector met 3-d geprinte muurelementen anders ontwerpen dan met conventionele wanden. Ook is 3-d printen belangrijk omdat het verschillende ontwerpmethodologieën biedt, zoals parametrische modelleren. Met andere woorden, de technologie ontwerpt niet echt, maar eerder script algoritmen die op verschillende bouwniveaus kunnen worden toegepast. Deze algoritmen kunnen vervolgens worden gebruikt om het ontwerpproces te ondersteunen en dat er mogelijk meer dan 400 miljoen verschillende soorten vormen per dag kunnen worden gemaakt, wat een interessante innovatie is. Afgezien van procesinnovatie, toonden interviewbevindingen ook aan dat individuen ook sociaal innovatief moeten zijn om het beste uit de 3-d printtechnologie te halen. De technologie is gebaseerd op drie aspecten, waaronder sociale innovatie, procesinnovatie en technische innovatie. In de tussentijd maakten de interviewresultaten ook duidelijk dat 3-d constructieprinten commercieel haalbaar is mits het toegepast wordt, wat impliceert dat het gebruik ervan bouwondernemingen in staat stelt een betere kans te maken om de bouwkosten aan te pakken. Over het algemeen nemen de kosten per product voor 3-d constructieprinten enorm af. Met de technologie is er ook de keuze voor off-site en on-site printing-objecten die een waarde propositie kunnen zijn. Bij conventionele constructie liggen de faalkosten tussen 5 en 25%. Wanneer dit naar de consument wordt vertaalt, krijgt de consument een architectuur die beter voldoet aan zijn behoeften op de gevraagde functionaliteit. Schaalbaarheid is net zo belangrijk voor het 3-d geprint product als voor het materiaal zelf.

De manieren waarop 3-d printtechnologie bedrijfsmodellen beïnvloedt, was ook een belangrijk gespreksonderwerp in de interviews. Volgens de geïnterviewden overwegen veel bedrijven die actief zijn in de bouwsector de laatste tijd de invoering van 3-d printtechnologie. Deze bedrijven zijn geïnteresseerd in verschillende modellen. Een goed voorbeeld is een bedrijf dat in samenwerking met partners een printtechnologie heeft ontwikkeld. Net als de hoofdaannemer ontwerpen, construeren, printen, produce en verkopen elelementen. Een ander bedrijf richt zich op het ontwikkelen van 3D-printers en verkoopt deze aan bedrijven, maar het is niet hun hoofddoel. Dit bedrijf werkt samen met zijn technologie afdeling die klanten ondersteund bij het printen, ontwerpen en construeren van complete gebouwen, inclusief wanden, vloeren en andere onderdelen. In bepaalde landen waar bedrijven niet helemaal vertrouwd zijn met 3-d printtechnologie, heeft het bedrijf in kwestie richtlijnen gegeven op verschillende toepassingsniveaus. Op het moment wordt 3-d constructieprinten gebruikt voor op maat gemaakte en complexe ontwerpen. Dus als er verder ontwikkeld is en de leercurve is ook verbeterd, zal uiteindelijk 3-d constructie printen worden gebruikt voor eenvoudigere ontwerpen.

Volgens de geïnterviewden is 3-d printtechnologie meer een geïntegreerde ontwerpoplossing. De innovatie combineert ontwerpengineering en productie tot een enkel systeem. Ook is de technologie gebruikersvriendelijk en in het algemeen effectief in termen van toepasbaarheid. Bovendien maakt de technologie engineering ontwerpen en produceren snel en gemakkelijk. Sommige geïnterviewden, zoals geïnterviewde 1, stelden echter dat als een andere technologie die beter lijkt dan 3-d printen verschijnt, deze automatisch wordt omarmd. Geïnterviewde 6 stelde dat andere niet-cementgebonden materialen in ontwikkeling uiteindelijk cementhoudende materialen overbodig zouden maken. De geïnterviewde vermeldt echter ook dat cementachtige materialen mogelijk nog steeds het voorkeursmateriaal kunnen zijn voor 3-d geprinte hoogbouw. In termen van gebruik voor innovatieve doeleinden, toonden interviewbevindingen aan dat de technologie wordt geïntegreerd met het robotsysteem en andere technologieën om de effectiviteit te verbeteren. Robotica betekent juiste software. Additieve productie vereist in het algemeen methoden om het ontwerp voor de additieve productie te snijden en te verwerken. Niettemin is een deel van de grootste zorg dat veel architecten die met conventionele bedrijven werken, geen ervaring als constructie ingenieurs hebben en dus liever conventioneel dingen doen. Bouwprojecten die worden gecoördineerd door mensen die werken met conventionele bedrijven zijn niet alleen tijdrovend; ze zijn ook duur. Een meerderheid van deze bedrijven zal beweren dat 3-d printen niet in de nabije toekomst volledig kan worden overgenomen omdat het erg duur is. De oplossing ligt echter in de bereidheid om informatie te vergroten binnen productie-, engineering- en ontwerpprocessen.

Uit de resultaten van het interview bleek ook dat, ondanks de mogelijkheden, de kenniskloof over 3-d printtechnologie een kritische barrière vormt die de goedkeuring en implementatie ervan problematisch maakt. Belemmeringen die worden geassocieerd met het gebruik van 3-d printen voor het ontwerp van een cementachtige buitenmuur kunnen worden aangepakt door constructie ingenieurs en architecten in dienst te nemen en het bewustzijn van de technologie te vergroten. Dientengevolge heeft de 3-d printtechnologie de conventionele constructiebenaderingen op verschillende manieren veranderd. Het is bijvoorbeeld nu mogelijk om bouwontwerpen te modelleren in plaats van ontwerpen te schetsen. Gebrek aan goede standaardisatie heeft het 3-d printen bemoeilijkt omdat sommige mensen niet zeker weten of de technologie veilig is of niet. In feite kunnen sommige voorschriften, zoals Europese regelgeving, alleen toestaan dat de technologie wordt gebruikt met zekerheid van de ontwerpen die worden getest. Dat betekent dat bouwbedrijven mogelijk geen goedkeuring krijgen of toestemming geven om bouwprojecten op gemeentelijk niveau te coördineren. Ondertussen is technologie geïdentificeerd als de fundamentele oplossing voor vele uitdagingen die worden geconfronteerd in de bouwsector, waaronder belemmeringen in typologie.

Volgens de geïnterviewden heeft de adoptie en implementatie van 3-d printen meerdere voordelen. De algoritmen zullen het proces managen, niet de mens. Mensen gaan van uitvoerende rollen naar coördinatieve rollen. Dit zal voor minder faalkosten zorgen die vertaald worden in kosten besparingen of betere aansluiting op de wensen van de klant. Ook zal het zorgen voor minder vraag naar personeel. Wat betreft het disintermediërende vermogen van 3-d, merkten de geïnterviewden op dat de robot niet zozeer de reden maar een verplichte oorzaak voor de parallellisatie is. Bovendien is 3-d constructieprinten niet de enige methode. In plaats daarvan is het een methode in het rijk van digitale fabricage en dat met robots er een breed scala aan mogelijkheden is. 3-d constructieprinten is een schaalbaar product dat snel en betaalbaar is, mits goed toegepast. Het materiaal is relatief betaalbaar, wat betekent dat het gebruik ervan relatief concurrerender maakt in vergelijking met conventionele methoden. Geïntegreerd ontwerp in combinatie met 3-d constructieprinten en andere digitale fabricagemethoden is innovatief. Je kunt verschillende muren en verschillende vormen maken, waardoor het bouwproces over het algemeen gemakkelijker wordt, zelfs in de moeilijkste gebieden om te bouwen zoals moerassige gebieden of plaatsen waar de grond zacht is. Je kunt betere buitenmuren bouwen, maar ook betere fundamenten met een 3D-constructieprinter omdat je er niet direct het volledige gewicht op legt. Met de technologie is het mogelijk om meer aantrekkelijke gebouwen te maken zonder de extra kosten. Het 3-d constructieprinten is uitstekend om zeer complexe vormen te creëren met de mogelijkheid van ventilatie of isolatie of warmtedissipatie, omdat het proces de mogelijkheid geeft om een huid te creëren en om een membraan te creëren dat veel meer op maat gemaakt is voor het milieu. Er is vertrouwen in het feit dat 3-d constructieprinten de bouwwaardeketen in de nabije toekomst verandert, maar voornamelijk maakt het deel uit van een parallelle waardeketen. Het meest interessante aan grootschalige 3-d printen is het feit dat materiaal kan worden om functionaliteit toe te voegen. Normaal gesproken gebeurt dit door gelaagdheid, dus het maken, stapelen van extra materialen op elkaar om bepaalde soorten eigenschappen te creëren, zoals isolatie, sterkte, waterbestendigheid en al dat soort dingen.

Terugkijkend op de schaalbaarheid van 3-d constructie printen van een cementachtige buitenmuur, heeft het potentieel, maar een volledig product is nog niet bereikt dat ook bewezen is om schaalbaar te zijn. Een volledig geautomatiseerd en geïntegreerd proces om een gespecificeerde muurtypologie te printen is nodig. In dit geval zou dit de typologie zijn van een 'geavanceerde versterkte cementgebonden muur' op pagina 53. 3-d constructieprint voorbeelden van deze typologie zijn 3DCP (TU Eindhoven), Thin Folded Concrete Members (ETH Zürich), Shotcrete 3-d printer (TU Braunschweig). Er wordt gesuggereerd dat het 3DCP-project het meeste potentieel heeft qua schaalbaarheid in de kortere termijn tijdspanne. Interviewers stelden echter ook dat dit te maken heeft met het vinden van de 'hot zone' in schaalbaarheid met betrekking tot het bedrijfsmodel. Onder deze voorbeelden is het voorbeeld van de 3DCP-printer de eenvoudigste versie; wat een goede zaak is in termen van schaalbaarheid. Met betrekking tot de 3-d constructieprinter wordt gesuggereerd dat deze 'hot zone' een volledig geïntegreerde digitale keten is waar de printer onderdeel van is. Binnen deze keten gaan mensen van uitvoerende rollen naar coördinerende rollen. Om bij te dragen aan het oplossen van de onderzoeksproblemen, moet schaalgrootte worden bereikt en daarom moeten grote bedragen aan investeringen worden aangetrokken.

Met betrekking tot de vijf schaalbaarheidsaspecten van Nielsen et al. (2018), de eerste tekenen van nieuwe distributiekanalen zijn er (meestal gedigitaliseerde en geïntegreerde kanalen), 3-d constructiebedrijven kunnen worden beperkt door traditionele capaciteitsbeperkingen zoals banen te korten in de bouwsector. Tijdens de interviews werd duidelijk dat kapitaalinvesteringen worden uitbesteed aan partners die effectief deelnemer werden in het bedrijfsmodel. Ook was het duidelijk dat klanten en andere partners meerdere rollen spelen in het bedrijfsmodel. Ten slotte hebben de interviews niet aangetoond dat er een duidelijk platformmodel is, waarbij concurrenten klanten kunnen worden, wat essentieel is in termen van schaalbaarheid.

Uit interviews bleek dat er een commitment is om in sommige bedrijven te groeien. Veel technologieën bevinden zich echter in de onderzoeksfase aan universiteiten en het was duidelijk uit de interviews dat de meeste onderzoekers niet wisten van businessmodel innovatie of schaalbaarheid van het bedrijfsmodel. Het zou ertoe bij kunnen dragen dat de onderzoeker gemotiveerd raakt over het ondernemersaspect van dingen zoals het geven van workshops door incubators die nauw contact hebben met de universiteiten. Dit draagt bij aan het derde aspect van brede managementvaardigheden en een nuttig mentorschap dat een cruciaal aspect is van de schaalbaarheid van een organisatie. Daarom moet de leercurve worden verbeterd, en de oplossing ligt in de bereidheid om informatie te vergroten binnen productie-, engineering- en ontwerpprocessen.

Bovendien is er een gebrek aan goede standaardisatie, wat een ander kritisch aspect is in termen van schaalbaarheidsproblemen (Coutou, 2014). Het verschil in regelgeving en verschil in digitalisering per land maken het ook erg moeilijk om te opereren en beperkt de schaalbaarheid van 3-d constructieprinten. Gesuggereerd wordt dat momenteel, het duidelijk is welk materiaal het juiste materiaal is in termen van schaalbaarheid; Cementgebonden materialen. In de interviews is echter gebleken dat er ook gedachtescholen zijn die een technisch onderbrekingsrisico op materialen kunnen veroorzaken. De school van gedachten kan worden beschreven in termen van (1) 3-d constructieprinten met conventionele materialen of (2) met volledig nieuwe materialen. De eerste is logisch vanuit een schaalperspectief, vanwege de kennis die mensen hebben die het materiaal kunnen ontwerpen, engineeren en construeren. Dit laatste is logischer vanuit een holistisch oogpunt; nieuwe technologie heeft een nieuwe manier van denken nodig en daarom heeft het nieuwe print materialen nodig die beter aansluiten op de behoeften van de klant. Dit laatste is echter minder schaalbaar op de kortere termijn, omdat er nog steeds een aanzienlijke kennisleemte is van de nieuwe materialen zoals FLAM of het gebruik van polymeren.

Terugkijkend op de adoptie van 3-d constructieprinten met cementachtige materialen, is het duidelijk dat we nog steeds de 'Chasm' (kloof) moeten overbruggen en door ons te concentreren op de gestelde schaalbaarheidsproblemen, kunnen we de kloof potentieel overbruggen. Bovendien zal alleen dan 3-d constructieprinten bijdragen aan het oplossen van de klimaatverandering, de uitputting van natuurlijke hulpbronnen en sociaal-economische factoren (Moore, 2014).

3.5.2 Resultaten van de vragenlijst

De vragenlijst leverde kritische informatie over de duurzaamheid, toepasbaarheid en acceptatie van 3-d printen in de bouwsector. De vragenlijst was zodanig gestructureerd dat verschillende belemmeringen, zoals bijbehorende kosten, gereedheid voor de invoering van de technologie, technische uitdagingen en andere indicatoren die de invoering van 3-d printtechnologie in de bouwsector konden verhinderen, waren gemeten. Terwijl de vragenlijsten naar meerdere mensen werden gestuurd, reageerden slechts 9 mensen. Dit vereiste een bootstrapping framework om de resultaten van de studie te extrapoleren en de overdraagbaarheid te garanderen. Het onderzoek liet zien dat hoge printerkosten een van de obstakels vormen voor effectieve acceptatie van 3D-printen in de bouwsector. Ondanks het feit dat de technologie nog nieuw is in Nederland, maakt het onvermogen van belanghebbenden in de bouwsector om aan de hoge kosten van printers te voldoen adoptie uitdagender. De eerste stap in het aanmoedigen van mensen om de technologie toe te passen en hiervan te profiteren, is door kostenkwesties aan te pakken. Enquêteresultaten droegen ook bij aan het feit dat hoge kosten van gedrukte structuren deel uitmaken van de belangrijkste uitdagingen die de toepassing van 3-d printen in de bouwsector problematisch maken. Daarom is het belangrijk voor experts in de branche en, nog belangrijker, voor vernieuwers om te heroverwegen en daarme de technologie nog verder te (her)ontwikkelen om het zo te kunnen kapitaliseren en toepasbaar te maken voor individuen en bedrijven die actief zijn in de bouwsector. Verder, in de analyse, onderzocht de studie het effect van commerciële levensvatbaarheid. Uit de analyse slaagden de 9 respondenten er niet in een consensus te bereiken over de implicaties van commerciële levensvatbaarheid voor de acceptatie van 3-d technologie (een gemiddelde van 3,8 tegen de drempelwaarde van 4). Uit de geëxtrapoleerde gegevens blijkt echter dat een gebrek aan commerciële levensvatbaarheid een belemmering vormt voor de acceptatie van 3-d printtechnologie in de bouwsector (bovengemiddelde waarde van 4,74 bij 95% CI tegen een drempelwaarde van 4). Omdat het creëren van een duurzame oplossing voor het probleem van vitaal belang is, moeten belanghebbenden in het veld die van invloed zijn op de commerciële levensvatbaarheid, kijken naar de oorzaak van ineffectiviteit en antwoorden bieden. Eveneens, van de evaluatie van het effect van technologieonderbreking tot de acceptatie van 3-d printtechnologie in de bouwsector, behaalde het onderzoek een gemiddelde waarde van 3,2 tegen een drempelwaarde van 4 voor de 9 deelnemers, wat impliceert dat veel van de deelnemers faalden Technologieonderbreking beschouwen als een struikelblok voor de toepassing van 3D-printtechnologie in de gebouwde omgeving. Extrapolatie van de gegevens met behulp van een bootstrapping-steekproef van 80 respondenten realiseerde echter een bovengemiddelde waarde van 4,37 tegen de drempelwaarde van 4, wat impliceert dat veel van de respondenten voor een grotere steekproef technologieonderbreking zouden hebben gezien als een nadeel van de goedkeuring van 3-d printtechnologie in de gebouwde omgeving. Als er iets is, moeten er meer experts en middelen worden gereserveerd om het vermogen te vergroten om in de toekomst met de barrière om te gaan. Hoewel de behoefte aan speciale materialen werd verondersteld als een mogelijke belemmering voor het gebruik van 3-d printtechnologie in de bouwsector, bleken de resultaten van de vragenlijst iets anders te zijn. Voor het monster van 9 personen werd een gemiddelde waarde van 2,62 verkregen, waardoor het effect niet als een obstakel kon worden gekwantificeerd.

Zelfs voor de geëxtrapoleerde gegevens met een steekproef van 80 deelnemers, behaalde de analyse een bovenste gemiddelde waarde van 3,37, wat nog steeds lager is dan de drempelwaarde van 4. De analyse kon dus niet vaststellen wat de implicaties waren van speciale materialen bij de adoptie van 3-d printtechnologie in de bouwsector. De bevindingen uit de vragenlijst brachten verder dat het vinden van de juiste nichemarkt geen uitdaging was om 3-d printen in de bouwsector aan te nemen. Uit de statistische analyse gaf een steekproef van 9 respondenten een gemiddelde waarde van 2,5 tegen een drempelwaarde van 4, waardoor het effect niet werd gerechtvaardigd als een belemmering voor de adoptie van 3-d printtechnologie. Een geëxtrapoleerde dataset met een steekproef van 80 respondenten bereikten verder een hogere gemiddelde waarde van 3,75 (95% CI), die nog steeds lager is dan de waarde van 4 (enigszins mee eens). De resultaten geven aan dat architecten, bouwmanagers en andere professionals moeten begrijpen dat de juiste markt alleen kan worden gerealiseerd door effectieve marketing en andere waardetoevoegingsstrategieën. Er is een potentiële markt voor 3-d printen die nog niet is onderzocht. Bevindingen uit de vragenlijst hebben ook duidelijk gemaakt dat een gebrek aan klantenondersteuning niet moet worden beschouwd als een significante belemmering die de acceptatie van 3-d printen in de bouwsector een probleem maakt (een gemiddelde waarde van 3,37 tegen 4 voor 9 respondenten) en een geëxtrapoleerd bovenste betrouwbaarheidsgemiddelde van 4,5 met een steekproef van 80 respondenten. Daarom is klantenondersteuning noodzakelijk om verschillende aspecten van het implementatieproces te ondersteunen; meer inspanningen moeten worden gericht op het vinden van duurzame oplossingen voor gerelateerde uitdagingen. Bovendien zijn er onvoldoende succesvolle voorbeelden van gebouwen die zijn gebouwd met behulp van 3-d printersoftware struikelblokken die de moeite van het adopteren van de technologie in de bouwsector een uitdaging maken. Uit het interviewgedeelte gaf 60% van de respondenten aan dat het gebruik van 3-d printen nog in de kinderschoenen staat en dat er initiatieven van belanghebbenden, overheden en professionals uit de bouwsector nodig zijn om samen te werken om manieren te vinden om de uitdagingen aan te gaan. In overeenstemming met de bevindingen uit de vragenlijst werden de bijbehorende kosten beschouwd als een kritieke hindernis voor het gebruik van 3-d technologie in de gebouwde omgeving.

3.6 Conclusies

Uit de bovenstaande resultaten blijkt dat 3-d printen (in combinatie van de geïntegreerde processen) een innovatieve technologie is met de capaciteit om de bouwsector te transformeren mits de barrières worden overwonnen en dit zijn er nog steeds aanzienlijk veel. Het adopteren en implementeren van 3-d printen heeft bijvoorbeeld meerdere voordelen. Bovendien is 3-d printen uitstekend om zeer complexe vormen te creëren met de mogelijkheid van ventilatie of isolatie of warmtedissipatie, omdat het proces van de mogelijkheid een huid te creëren en een membraan te creëren dat veel meer op maat is gemaakt voor het milieu of de omgeving. De belemmeringen die de invoering van de technologie vertragen, moeten echter worden aangepakt voor toekomstig succes. Hoge printerkosten, hoge kosten van gedrukte structuren, gebrek aan commerciële levensvatbaarheid en andere factoren vormen een aanzienlijke belemmering voor de invoering van de technologie. Dus bij het vaststellen van duurzame oplossingen, moeten deze kwesties prioriteit krijgen. Interessant genoeg zijn er voorbeelden gegeven waarbij het al kosteneffectiever lijkt of andere waardeproposities bieden die suggereren dat er al 'first movers' (vroege overstappers) zijn in de 3-d constructieprint industry, maar in het algemeen is de gebouwde omgeving zich hiervan niet bewust. Er wordt echter gesuggereerd dat deze partijen op de een of andere manier nog steeds te maken hebben met de gegeven belemmeringen. Ook blijkt uit de statistische analyse dat de meeste belemmeringen uit de literatuurstudie nog steeds bestaan. Het interessante is dat uit de interviews is gebleken dat er potentieel is. Er wordt gesuggereerd dat dit potentieel kan worden ontdekt in de combinatie van de (3-d printing) technologieën. Daarom wordt er gesuggereerd dat 3-d constructieprinten schaalbaar kan worden als de voorgestelde barrières en de onontdekte barrières in deze thesis worden overwonnen. De onontdekte barrières zijn vooral te vinden in sociale innovatie, procesinnovatie en technische innovatie met name in de 3-d constructieprinting techniek als voor het te printen materiaal zelf.

Uit de resultaten en bevindingen wordt gesuggereerd dat het grote struikelblok dat de acceptatie van 3-d printen in de bouwsector voorkomt, is het ontbreken van grote groepen mensen die zich kunnen inzetten om de technologie vooruit te helpen. De meest voor de hand liggende reden hiervoor is het gebrek aan financiële prikkels om kennis te bevorderen over hoe 3-d printen werkt en hoe deze kunnen worden toegepast in de bouwsector. Daarom wordt gesuggereerd dat het gestelde innovators-dilemma van Christensen (1997) geldig blijft voor het gros van de bedrijven. Alleen als deze problemen worden overwonnen, draagt 3-d constructieprinten mogelijk bij aan het oplossen van klimaatverandering, de uitputting van natuurlijke hulpbronnen en sociaal-economische factoren (Moore, 2014).

3.7 Aanbevelingen

- Significante en niet-significante belemmeringen die van invloed zijn op de acceptatie van 3-d printen in de bouwsector, moeten verder worden geëvalueerd op basis van de bevindingen van deze studie en een onderscheidingslijn moet gemaakt worden tussen beide voor prioritering.
- Verder onderzoek zou moeten worden uitgevoerd om meer inzichten en informatie te verschaffen over hoe 3-d constructie printen werkt en hoe deze met gemak in de bouwsector kunnen worden toegepast.
- Stakeholders in de bouwsector moeten waar mogelijk samenwerken om het succes van de acceptatie van 3-d printtechnologie in de sector noodzakelijk te maken.
- Technologische belemmeringen moeten worden aangepakt om de weg vrij te maken voor een effectieve invoering van 3-d constructieprinten in de bouwsector.
- Er is meer onderzoek nodig naar de schaalbaarheid van gebruikte materialen en 3-d printtechnologieën.

3.8 Referenties

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4 Summary

4.1 Abstract

Various technologies in the domain of digital fabrication have been introduced in the construction industry to promote efficiency. This thesis provides a platform for reviewing 3-d construction printing technology. This thesis explored the barriers that make the adoption of 3-d printing technology in the construction industry difficult. The significance or effects of these barriers will be evaluated by assessing the positions and views of the study participants. These barriers include:

- High costs of printer.
- Immaturity of printing partners.
- Unclear regulatory implications.
- Inability to create larger structures.
- High cost of printed structures.
- Lack of commercial viability.
- Lack of customer support.
- Lack of sufficient successful examples.
- Architect/designer unpreparedness.
- Difficulty of transporting printers.
- Technology interruption risk.
- Need for expensive specialty materials.

The three suggested problems climate change, depletion of natural resources and socio-economic factors are all considered important which is quite broad if not explained with a good point of

departure. However, the point of departure of this thesis is that it is about attributing to the solving of these 3 big problems (national and even world problems). And that scalability of a product and thus mass feasibility of 3-d printing is crucial for worldwide adoption and solving real-world issues instead of just creating a niche market for free-form architecture. When a product is highly scalable and brings real value, assumable big private (and even public) investments can be attracted if the product makes sense from an investor point of view. Therefore, 3-d construction printing really needs to add value on a larger scale and not just for a niche market on the longer term. It should be clear to see if big investments are worthy for 3-d construction printing. Besides, I wanted to learn how to research a new product for myself and on its potentials for providing a solution for important (world) issues. In short, there are potential new materials, there are barriers and I research the way how barriers can be discovered and potentially be overcome in the domain of digital fabrication, focusing on cementitious 3-d construction printing.

The thesis was divided into different parts. The first section is an introduction from where the topic was introduced. The next part covered the research methods and more importantly, the techniques that were used to gather data and information from the study participants. From there, main research results were provided. Here, the results were divided into interview results and questionnaire results. Subsequently, a brief conclusion that summarized the main parts of the paper was be provided followed by possible recommendations.

4.2 Keywords

Digital fabrication, 3-d construction printing, FLAM, Robotics, Algorithms

4.3 Introduction

Technological innovation has been the foundation of effectiveness and success in many industries. However, the issue of adoption has always been emerging as a core subject of concern because of possible barriers that block implementation. 3-d printing is an emerging technology that is yet to be fully adopted in the construction industry. For the record, if applied properly, the technology is way off better than conventional construction method because it is cost-effective and efficient. Therefore, this research focuses at determining possible reasons that might be making the adoption of the technology in the construction industry to be generally difficult. The study will revolve around the possible barriers that have been singled out in other researches or by other experts working in the construction industry and use questionnaires and interviews to determine whether the barriers are significant or not. From there, a brief conclusion and possible recommendations on way forward could be provided.

4.4 Research Methods

The research methods that were used in this research included the use of questionnaires and interviews. Interviews that lasted for 50 minutes were conducted where 9 experts were interviewed. The telephone call was taped and later on transcribed into a word document to enhance understanding. Questionnaires, on the other hand, were developed and distributed to different study participants. The questionnaire revolves around 12 important areas that are believed to be possible barriers towards the adoption of 3-d printing technology in the construction industry. Meanwhile, all study participants including those people who were interviewed and those who responded to the questionnaires were reminded about the ethical values of the research. For instance, they were all reminded that their privacy will be protected. Also, the participants were told that they can participate in the study willingly and in case they want to pull out, they should not hesitate to do so if it will make them comfortable.

4.5 Main Research Results

4.5.1 Interview Results

Interview results from the participants provided more insights about the gravity of the issue of 3-d printing and its adoption in the construction industry. While trying to find out how FLAM (Fungal-Like Adhesive Material) can be integrated successfully into a 3-d printed cementitious outer wall as well as things to do with insulation effects and cost of such an approach, interview results showed that attention is being redirected at printing concrete and that FLAM is a new material that can potentially be added to the outer wall or as additive in the cementitious material. The actual cost being incurred with the use of FLAM is the cost that is involved in replacing sand or other materials. FLAM is some kind of a buffer and that increases insulation value because it has the same structural properties or features like that of materials that look like wood (Sanandiya, 2018). However, in the Netherlands, that will mean that the wall element should probably be comprised of a huge thick wall. FLAM can assumable used like a conventional insulation that one might need for materials like bio-pearls. The material has significant effect on the printability of a material in relation to probability because one has to end up with a printable material. Interview results also saw the interviewees citing FLAM as sustainable and a great way that people in the construction industry can utilize to help reduce carbon emissions. Part of the information that was shared to the interviewees was that the cost of FLAM is less than 2$/kg, similar to commodity plastics and is 10 times lower than the cost of common filaments for 3-d printing. This material can also be used to 3-d print large structures for objects such as an outer wall' (Fernandez, 2019). Thus, according to the interviewees, it is possible to create a passive structure with very well optimized to parametrize insulation capabilities according to the latitude of the application. The same building, the same outer wall might be tailored for the particular climate condition zone by zone, climate by climate. The cementitious material has been for a long time something quite far away, for instance, from machines. Engineers used to talk about concrete and not talk about the raw materials behind. There are a lot of entities who might be intrigued to promote the realization of outer walls recycling materials and the second-hand material which was unheard possibilities until the augment of 3-d printing.

In retrospect to the scalability of this material, there is potential to scale this product. However, none of the interviewees heard of FLAM before, and they did not know yet on how it would act in the real world. This is no surprise because the research is published at the end of 2018. However, one interviewee did have valuable knowledge of other biodegradable and ecologically sustainable materials. According one interviewer PETG (+-$18,-/kg), PVDF (+-$18,-/kg) and ASA (+-$4,5/kg) are potential polymer based 3-d printing construction materials. These materials are finer to print with than cementitious materials, have better design capabilities than conventional materials, are sustainable and 3-d printed houses is a possibility. However, 3-d printing high rise buildings, which has a higher building density than family houses, is currently not possible with polymers and therefore it is currently far less scalable than cementitious materials. Moreover, it can be concluded that there is a practical knowledge gap of FLAM (and other polymer based materials), the articulation of competitive strength is not thoroughly considered yet and there exists a lack of standardization of FLAM. Therefore, it is clear that these factors act as barriers to the scalability of FLAM (Coutu, 2014; Nielsen et al., 2018).

The interview results also provided a basis for exploring the innovative capacities of 3-d printing with reference to the function and design of a cementitious wall. According to them, 3-d printing allows people in the construction industry to design wall elements differently from the design of conventional walls. Also, 3-d printing is important because it provides different designing methodologies such as parametric modeling. In other words, the technology does not actually design, but rather script algorithms that can be applied at different construction levels. These algorithms can then be used to aid the designing process and that one can possibly end up with more than 400 million different kinds of shapes per day, which is an interesting innovation. Other than process innovation, interview findings also showed that individuals should also be socially innovative to get the best out of 3-d printing technology. The technology is based on three aspects including social innovation, process innovation, and technical innovation. In the meanwhile, the interview results also made it clear that 3-d construction printing is commercially feasible when applied correctly, implying that its use can enable construction companies to have a better chance of addressing construction costs. Generally speaking, the cost per product for 3-d construction printing is decreasing enormously. With the technology, there is also the choice for off-site and on-site printing objects which can be a value proposition. In conventional construction, the failing costs are between 5 and 25%. When you translate this to the consumer side, then the consumer will get an architecture which will fit better to its needs on the demanded functionality. Scalability is equally important for the 3-d printed product as for the material itself.

The ways in which 3-d printing technology affects business models was also an important area of discussion in the interviews. According to the interviewees, many companies operating in the construction industry are considering the adoption of 3-d printing technology lately. These companies are interested in different models. A great example is a company which developed a printing technology in collaboration with partners. Just like the general contractor, these companies design, engineer, print, produce and sell those model elements. Another company focuses on developing 3-d printers and sells them to companies but it is not their main focus. This company operates with its technology department who assist in printing, designing and engineering entire buildings including walls, floors and other parts. In certain countries where companies are not entirely conversant with 3-d printing technology, the company in question has been providing guidance at different applicability levels. As of now, 3-d construction printing is used for customized and complexed design. Hence, if further developed and the learning curve is as well enhanced, eventually 3-d construction printing will be used for simpler designs.

According to the interviewees, 3-d printing technology is more of an integrated design solution. The innovation merges design engineering and production into a single system. Also, the technology is user friendly and generally effective in terms of applicability. In addition, the technology makes engineering designing and production fast and convenient. However, some interviewees like interviewee 1 stated that if another technology that appears to be better than 3-d printing emerges, it will be embraced automatically. Interviewee 6 stated that other non-cementitious materials in development would eventually make cementitious materials redundant. However, the interviewee also mentions that cementitious materials could potentially still be the preferred material to 3-d print high-rise buildings. In terms of being used for innovative purposes, interview findings demonstrated that the technology is being integrated with the robotic system and other technologies to enhance effectiveness. Robotics means right software. Additive manufacturing is generally requiring methods to slice and to process the design for the additive manufacturing. Nonetheless, part of the main concerns is that many architects working with conventional companies lack experience as structural engineers and thus, they prefer doing things conventionally. Construction projects that are coordinated by people who work with conventional companies are not only time-consuming; they are also costly. A majority of these firms will argue that 3-d printing cannot be fully adopted in the near future because it is very expensive. However, solution lies with the willingness to increase information within production, engineering and design processes.

Interview results also proved that despite its capabilities, knowledge gap on 3-d printing technology is a critical barrier that makes its adoption and implementation problematic. Barriers that are associated with the use of 3-d printing for the design of cementitious outer wall can be addressed by hiring structural engineers and architects as well as promoting awareness on the technology. Consequently, 3-d printing technology has changed the conventional construction approaches in multiple ways. For instance, it is now possible to model building designs rather than going for sketches. Lack of proper standardization has made 3-d printing difficult to adopt because some people are not sure whether the technology is safe or not. In fact, some regulations such as European regulation can only allow the technology to be used with assurance of the designs that are being tested. That means that construction companies might fail to get approval or permit to coordinate construction projects at the municipality level. In the meanwhile, technology has been identified as the fundamental solution to many challenges that are being faced in the construction industry including barriers of typology.

According to the interviewees, the adoption and implementation of 3-d printing will have multiple advantages. The algorithms will manage the process and not people. People will go from executive roles to coordinative roles. This will result in less failing costs or creating the opportunity to better meet the wishes of the client. Also, it will reduce the need for personnel. In terms of disintermediating capability of 3-d, the interviewees noted that the robot is not so much the reason but a mandatory cause for the parallelization. Moreover, 3-d construction printing is not the one method. Instead, it is a method in the reign of digital fabrication and that with robots, there is a wide range of possibilities. 3-d construction printing is a scalable product that is fast and affordable when applied correctly. The material is relatively affordable meaning that adopting it will make it more competitive compared to conventional methods. Integrated design in combination with 3-d construction printing and other digital fabrication methods is innovative. You can make different walls and different shapes thus making construction process generally easier even in the most difficult areas to build such as swampy areas or places where the soil is soft. You can build better outer walls, but also better fundaments with a 3-d construction printer because you don't directly put the fully weight on it. With the technology, it is possible to create more appealing buildings without the extra costs. The 3-d construction printing is excellent to create very complex shapes with the capability of ventilation or insulation or heat dissipation because the process of the possibility to create a skin and to create a membrane much more tailored for the environment. There is confidence in that 3-d construction printing is altering the construction value chain in the near future, but mostly it is part of a parallel value chain. The most interesting thing about large scale 3-d printing is the fact that you can use material as a way of adding functionality. Normally this is done by layering, so making, stacking additional materials on top of each other to create certain kinds properties like insulation, strength, water resistance, all that kind of elements.

In retrospect to the scalability of 3-d construction printing a cementitious outer wall, it has potential, but a whole product has not been reached yet which is also proven to be scalable. A fully automated and integrated process to 3-d print a wall typology is needed. In this case, this would be the typology 'advanced reinforced cementitious wall' on page 53. 3-d construction printing project examples of this typology are 3DCP (TU Eindhoven), Thin Folded Concrete Members (ETH

Zurich), Shotcrete 3-d printer (TU Braunschweig). It is suggested that the 3DCP project has the most potential in terms of scalability in the shorter timeframe. However, interviewers also stated that this has to do with finding the 'hot zone' in business model scalability. Amongst these examples, the 3DCP printer example is the simplest version; which is a good thing in terms of scalability. Amongst the 3-d construction printer itself, it is suggested that this 'hot zone' is a fully integrated digital chain where the printer is part of it. Within this chain, people will go from executive roles to coordinative roles. To contribute to the solving of the research problems, scale must be attained and therefore, large sums of investments must be attracted.

Regarding the five scalability aspects of Nielsen et al. (2018), the first signs of new distribution channels are there (mostly digitalised and integrated channels), 3-d construction printed businesses can be limited by traditional capacity constraints such as employment scarcity within the built environment. It was clear through the interviews that capital investments are outsourced to partners who effectively became participants in the business model. Also, it was clear that customers and other partners play multiple roles in the business model. Lastly, the interviews did not show that there is a clear platform model, where competitors may become customers, which is essential in terms of scalability.

Interviews showed there is a commitment to grow in some companies. However, a lot of technologies are in the research phase at universities, and it was clear from the interviews that most of the researcher did not know about business model innovation or scalability. It would help to get researcher more motivated on the entrepreneurial aspect of things such as providing workshops from incubators that have close contact with the universities, which brings it to the third aspect of broad management skill set and useful mentorship which is a critical aspect to the scalability of a business. Therefore, the learning curve must be enhanced, and the solution lies in the willingness to increase information within production, engineering and design processes.

Moreover, there is a lack of proper standardisation, which is another critical aspect in terms of scalability issues (Coutou, 2014). Also, the regulatory difference and digitalisation per country makes it very hard to operate and limits the scalability of 3-d construction printing. Currently, it is clear which material is the right material in terms of scalability; Cementitious materials. However, in the interviews was shown there are to schools of thought which can cause a technological interruption risk on materials. The school of thoughts can be described in terms of (1) 3-d construction printing with conventional materials or (2) with totally new materials. The former makes sense from a scaling point of view, due to the knowledge people have that can design, engineer and construct the material. The latter is more logical from a holistic point of view; new technology needs a new way of thinking, and therefore, it needs new printed materials which suit better to the needs of the client. However, the latter is less scalable on the shorter term since there is still a significant knowledge gap of the new materials such as FLAM or the use of polymers.

In retrospect to the adoption of 3-d construction printing with cementitious materials, it is clear we still need to bridge the 'chasm', and by focussing on the posed scalability issues, we can potentially bridge the chasm. In addition, only then 3-d construction printing will contribute to the resolving of climate change, the depletion of natural resources and socio-economic factors (Moore, 2014).

4.5.2 Questionnaire Results

The questionnaire provided critical information on the sustainability, applicability, and adoption of 3-d printing in the construction industry. The questionnaire was structured in a way as to measure various barriers such as associated costs, readiness for the adoption of the technology, technical challenges, among other indicators that could have impeded the adoption of 3-d printing technology in the construction industry. While the questionnaires were sent to several people, only 9 people responded. This necessitated a bootstrapping framework to extrapolate the results of the study and to ensure transferability. The study realized that high printer cost is one of the barriers to effective adoption of 3-d printing in the construction industry. Despite the fact that the technology is still new in the Netherlands, the inability of stakeholders in the construction industry to meet the high costs of printers makes adoption more challenging. The first step in as far as encouraging people to apply and capitalize on the technology is by addressing cost issues. Questionnaire results also added to the fact that high costs of printed structures form part of the main challenges that make the adoption of 3-d printing in the construction industry problematic. Hence, it will be important for experts in the industry and more importantly, innovators to consider redesigning the technology even further to make it cheap and convenient for individuals and companies that operate in the construction industry. Further, in the analysis, the study considered the effect of commercial viability. From the analysis, the 9 respondents failed to reach a consensus on the implications of commercial viability on the adoption of 3-d technology (a mean of 3.8 against the threshold of 4). However, the extrapolated data shows that lack of commercial viability is a barrier to the adoption of 3-d printing technology in the construction industry (upper mean value of 4.74 at 95% CI against a threshold value of 4). Because the creation of a lasting solution to the problem is vital, stakeholders in the field who are in the capacity of impacting commercial viability should look at the root cause of ineffectiveness and provide answers. Equally, from the evaluation of the effect of technology interruption to adoption of 3-d printing technology in the construction industry, the study obtained a mean value of 3.2 against a threshold value of 4 for the 9 participants, implying that many of the participants failed to consider technology interruption as a stumbling block to adopting 3-d printing technology in the built environment. However, extrapolation of the data using a bootstrapping sample of 80 respondents realized an upper mean value of 4.37 against the threshold of 4, implying that for a larger sample, many of the respondents would have viewed technology interruption as a drawback to adopting 3-d printing technology in the built environment. If anything, more experts and resources should be set aside to enhance the capability of dealing with the barrier in the future. While the need for specialty materials was hypothesized as a possible barrier to adopting 3-d printing technology in the construction industry, the questionnaire results proved otherwise. For the sample of 9 people, a mean value of 2.62 was obtained, failing to quantify the effect as an obstacle. Even for the extrapolated data using a sampled respondent of 80 participants, the analysis realized an upper mean value of 3.37, which is still lower than the threshold value of 4. Thus, the analysis failed to ascertain the implications of specialty materials in adopting 3-d printing technology in the built environment. The questionnaire findings further revealed that finding the right niche market was not a challenge to adopting 3-d printing in the construction industry. From the statistical analysis, a sample of 9 respondents gave a mean value of 2.5 against a threshold value of 4, thus failing to justify the effect as having a barrier to adopting 3-d printing technology. An extrapolated dataset using a sample of 80 respondents further realized a higher mean value of 3.75 (95% CI), which is still lower than the value of 4 (somewhat agree). The findings indicate that there is a need for architects, construction managers, and other professionals to understand that the right market will only be realized through effective marketing and other value addition strategies. There is a potential market for 3-d printing which has not been explored. Findings from the questionnaire also made it clear that lack of customer support should not be considered to be a significant barrier that makes the adoption of 3-d printing in the construction industry a problem (a mean value of 3.37 against 4 for 9 respondents) and an extrapolated upper confidence mean of 4.5 using a sample of 80 respondents. Therefore, in as much as customer support is necessary to aid different aspects of the implementation process; more effort should be redirected at establishing lasting solutions to related challenges. Furthermore, insufficient successful examples of buildings that have been constructed with the aid of 3-d printing software are stumbling blocks that are making the effort of adopting the technology in the construction industry a challenge. From the interview section, 60% of the respondents indicated that the use of 3-d printing is still in its infancy and there is the need for initiatives from stakeholders, governments, and construction industry professionals to come together to devise ways of overcoming the challenges. Consistent with the findings from the questionnaire associated cost was considered a critical barriers to adopting 3-d technology in the built environment.

4.6 Conclusions

From the above results, it is evident that 3-d printing (in combination with the integrated processes) is an innovative technology with the capacity to transform the construction industry when the posed barriers can be overcome. For instance, the adoption and implementation of 3-d printing will have multiple advantages. Additionally, 3-d printing is excellent to create very complex shapes with the capability of ventilation or insulation or heat dissipation because the process of the possibility to create a skin and to create a membrane much more tailored for the environment. However, the barriers that are slowing down the adoption of the technology should be addressed for future success. High printer costs, high costs of printed structures, lack of commercial viability among other factors are significant barriers towards the adoption of the technology. Thus, while establishing lasting solutions, these issues should be prioritized. Interestingly enough, there were examples given where it seems already more cost-effective or provide other value propositions which suggests there are already first movers in the 3-d printing construction market, but in general the built environment is not aware of this. However, is its suggested that these parties in some way still have to cope with the given barriers. Also, It is clear from the statistical analysis that most of the barriers from the literature review are still existent. The interesting part is, that the interviews showed there is potential. It is suggested that this potential can be discovered in the combination of the (3-d printing) technologies. Therefore, it is suggested that 3-d construction printing can become scalable if the proposed barriers and the undiscovered barriers in this thesis are overcome. The undiscovered barriers mostly can be found in social innovation, process innovation and technical innovation for the 3-d printing construction technology as for the material itself.

From the results and findings, it is suggested that the major stumbling block that prevents the adoption of 3-d printing in the construction industry is lack of large groups of people who can commit themselves to push the technology forward. Most assumedly, the reason for this is lack of financial incentive to necessitate the fostering of knowledge on how 3-d printing works and how it can be applied in the construction industry. Therefore, is it suggested that the posed innovators dilemma of Christensen (1997) remains valid for the gross of the companies. In addition, only if these issues are overcome, then 3-d construction printing will assumedly contribute to the resolving of climate change, the depletion of natural resources and socio-economic factors (Moore, 2014).

4.7 Recommendations

- Significant and non-significant barriers that affect the adoption of 3-d printing in the construction industry should be evaluated further basing on findings of this study and a line of distinction created between the two for prioritization purposes.
- Further research should be conducted to provide more insights and information on how 3-d printing works and how it can be adopted in the construction industry with ease.
- Stakeholders in the construction industry should collaborate where possible to necessitate the success of adoption of 3-d printing technology in the sector.
- Technological barriers should be addressed to pave the way for effective adoption of 3-d printing in the construction sector.
- More research is needed to the scalability of materials and 3-d printing technologies involved.

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Contents

5 Introduction

This section describes the underlying problems being addressed in this study, setting the research in the context of the construction and property industry. This section also sets the study in a wider societal context to highlight the relevance of this research. The study does not constitute a comprehensive response to the identified problems, which have been further discussed and delimited below.

5.1 A description of the research problem

A lasting solution to the problem of global warming is yet to be attained. Just like other world countries, the Netherlands should adopt techniques of reducing carbon emissions through and promoting environmental sustainability without affecting constructions profits and the country's needs for new buildings. Accordingly, this requires greater technology use and a high level of innovation in the construction industry. By so doing, the country will be able to reduce carbon footprint in a bid to comply with the European Union's environmental regulations and demonstrating global commitments. To attain radical reductions in carbon emissions, better industrial control is important. There is a pressing need for sustainable development to cater for economic and social needs of the society while at the same time ensuring that the natural environment has been preserved accordingly (Kibert, 2016; Nalewaik & Venters, 2008). Here, the fundamental aim is to have a sustainable *economy*. Apparently, a sustainable economy can only be attained through implementation of a circular economy in which materials are used as effectively as possible while retaining underlying value across the life cycle of individual products while meeting society needs. Moreover, the attainment of a circular economy can be made possible through four fundamental building blocks including enabling conditions like regulations and legislations, new business models, global reverse networks, and effective and efficient product and material design (Lewandowski, 2016). Essentially, multiple researches have demonstrated that this could not be attained without the application and implementation of innovative technology across the industrial sector including building and construction industry. The construction industry plays an essential role in national economy and has great effect on carbon emissions, climate change, depletion of natural resources, and the sustainability of the built environment (Nejat et al., 2015; Kibert, 2016).

According to Dijkstra (2016), Netherland's construction industry is responsible for 19% of transportation activities in the country as well as 37% of all generated wastes. Furthermore, the industry is responsible for approximately 4.5% of energy that is consumed in the country. The study also demonstrated that the construction industry consumes vast amounts of public investments that are made available to make the industry effective and productive. That means that the attainment of the goal of circular economy should include making the entire construction industry as sustainable as possible. Nonetheless, it is equally important to note that the fundamental reality is that the construction industry is inefficient, project-oriented, underproductive with immense amounts of projects being delivered over-budget and late. Also, the traditional construction process is generally slow so as to meet the corresponding demands for residential properties in the Netherlands thus subjecting both the community and the government to a lot of pressure. Atradius (2016) went a step further and added that levels of productivity in the Netherlands are low in the industry and profit margin in the construction organizations are continuing to deteriorate. Part of the greater problem is that the construction industry depends heavily on what is described as "take-make-use-dispose" sequence as well as the linear material economy business model. Some studies argue that more sustainable solution should be established through the three R's (Repair-Reuse-Recycle) (Ashby, 2015) by creating a good basis for shifting from what could be described as a linear economy to a circular economy. According to Lawson et al. (2014), this could be attained through application of innovative and creative processes like modular construction and off-site manufacturing.

Suggestions have been made citing a strong case for the utilization of innovative technology in the construction industry because it helps reduce wastes generated during the designing and construction process and at the same time offering a high level of design flexibility and optimization of effective material use. Various forms of pre-fabrication could be used in the construction industry including panelized units, volumetric units, or modular construction (Lawson et al., 2014). However, it is also vital to note that additive manufacturing and more precisely, 3-d printing is a technology that has just emerged and has been suggested to be a vital piece of solution in a far as reducing the levels of carbon emissions from the construction sector is concerned. In other words, proper utilization of the technology could play an essential role in promoting sustainability in the property sector and construction industry (Yossef & Chen, 2015).

Consequently, suggestions have been made stating that additive manufacturing could promote the logistics of building components thereby assisting in reducing carbon emissions at different levels of the construction process and at the same time enhance design flexibility with related cost reductions (Weller et al., 2015).

The established companies that have been described by Cayton and Christensen (1997) using innovator's dilemma resemble the construction industry. In the assessment, it is possible to see the way corporations are finding it difficult to adopt and implement disruptive technologies because it is unjustified and irrational call. A majority of established firms end up failing because they are not in the capacity to implement effective technologies that suits their operational undertakings. Part of the reasons for this general inability is emergence of new market demands that are difficult to address with the realization of this disruptive technologies (Clayton & Christensen, 1997).

With that in mind, it has been proposed that there are multiple advantages for choosing to explore the barriers of additive manufacturing in the construction industry. Redirecting attention at 3-d construction printing of the cementitious outer wall through close examination of these technological barriers and coming up with possible solutions for countering the issue will be a great move that can help promote sustainability in the construction industry. In addition, research will be very essential in this case because it will help unveil existing challenges and establish solutions that can be implemented through 3-d construction printing. It is especially vital that people who are building should consider changing their agendas and capitalize on 3-d printing technology where possible. That will be a massive step because challenges that are being experienced in the construction industry can be managed through the technology and as a result provide effective and workable guidance that can be used by different stakeholders in the industry to attain financially rewarding developments of high quality.

To begin with, the research problem exists in the context of the survival of companies. It is vital to understand that for corporations to survive, the top management officials and executive managers should be in a better position of considering repetitiously if it is a must they should promote innovation and creativity within the company. Thus, it is of great significance that market timings should be put into consideration for a specific new technology and more importantly, if it has to become successful in the environment. It is therefore very essential to have a coherent understanding of the barriers that are assumed to be technologically related because they are still significant to some extent. Being able to focus on the right barriers, possibilities of attaining success and establishing more value for future sustainability is attained. For instance, if a company wrongly assumes technological barriers and does nothing in response, its chances of failure increase. Apart from that, the research problem is present in a business domain that is rapidly changing in terms of design and technological interface. Until lately, there were few data and information that were available about the challenges of 3-d printing in the construction industry ((Xia & Sanjayan, 2016). However, the years 2017 and 2018 saw rapid expansion in information and literature on 3-d construction printing. However, the cornerstone of these studies were only limited to the insights that were provided to the actual company stakeholders including architects, clients and construction firms at large. Subsequently, part of rapid progress and maturation in 3-d printing have led to corresponding change in both focus and nature of challenges that people have to face while using the technology (Fadelli, 2018). For instance, this thesis has subsequently argued that early focus on technological feasibility of 3-d printing has changed significantly with a lot of attention being redirected at design lately. Even though pure barriers that can be categorized as technical are still there, maturation of 3-d printing in the building and construction industry implies that it is possible to raise questions about design attractiveness and related late-stage adoptions (Gosselin et al., 2016). Moreover, concerns are as well there regarding the type of materials and products that are feasible and effective with 3-d printing (Bos et al., 2016). In other words, our research problem has different unique design, technological and facets that are related to business activities. Notably, the research problem is delimited to materials that are cementitious and more precisely, the qualitative research questions that revolve around this study as well as cementitious outer walls. There are multiple reasons that can be used as the basis for explaining this delimitation. Firstly, cementitious materials are considered to be part of the most proven materials that are essential in the global construction industry. Secondly, there is a good record of 3-d construction printing that is being used for cementitious materials (Bos et al., 2016). Thirdly, there are vast materials and resources on cementitious materials. Fourthly, characteristics of cementitious materials provide a great chance for conducting study on both innovative potential as well as specific challenges and barriers that revolve around the use of 3-d construction printing.

5.2 Importance of Research Problem to the Society

There are multiple reasons as to why technological use like the utilization of additive manufacturing is essential at both society and industry level. For instance, technology use in the construction industry provides a remarkable basis for attending to matters to do with depletion of natural resources, climate change, and the need to increase the quality and supply of housing in the Netherlands (Koskela & Vrijhoef, 2001; Kibert, 2016; Lawson et al., 2014; Myers, 2016). As stated earlier on, the core goal of having a sustainable *economy* that reduces the effects of the built environment on the larger natural environment without necessarily compromising the natural environment is critical (Lewandowski, 2016). This research sheds light on creativity in the construction industry as a prerequisite for being in a better position of tackling these concerns. Moreover, closer review of the 3-d construction printing is as well required because as at now, it is in the innovator's stage and that the technology under consideration still needs to establish a link to bridge or bring together the chasm to eventuality or reaching out to the majority of the users and hopefully, contribute to what could be described as sustainable economy and effective housing supply in the Netherlands. According to Moore (2014), there are five stages that summarizes the adoption life cycle including innovators, early adopters, early majority, late majority and laggards. However, the bottom of it all is that the most important aspect that can be used to reach out to the chasm is to come up with what could be termed as a whole product (Moore, 2014). In this case, a whole product is regarded as the minimum set of services and products that are required to attain compelling reason for purchase by the target customer.

5.2.1 Climate Change

It has been argued that contributing to the resolving of the poor performance of the construction industry is essential through technology for three important reasons. First, the contemporary global society is yet to address the issue of global warming and climate change. Environmental experts have described this as a phenomenon that can possibly lead to warmer oceans and rising sea levels, loss of natural biodiversity, and melting of polar ice caps. Meinshausen et al. (2009) added that climate change could lead to increase in the possibility of experiencing extreme weather conditions including flooding and drought thus affecting water resources and food chain. In other words, the effects of climate change will become acute in almost all parts of the world regardless of whether human population is going to be affected directly or indirectly (Brandon & Lombardi, 2010). Hence, it has been argued that continuous use of working practices and materials that are effective including the utilization of modern construction techniques could help reduce material waste and at the same time improve energy efficient of the built environment with a corresponding consequential reduction in the level of carbon emissions.

5.2.2 Depletion of Natural Resources

A second reason why the use of innovative technology is required in the construction industry is the depletion of natural resources and the fact that the construction industry has a reputation for wasting materials (Von Blottnitz, & Curran, 2007; Maroto-Valer et al., 2012; Kibert, 2015). The reality is that there are high levels of waste within the construction industry and in the construction process - in part because of the fragmented nature of the industry (Fulford & Standing, 2014), and in part because of the use of wet-processes (Ann et al., 2013) and inadequate resource management on a project level (Ajayi et al., 2015). This research takes the view that waste can be reduced through the use of innovative methods of construction such as off-site manufacturing (Lawson et al., 2014).

Fadelli (2018) discussed 3-d construction printing in terms of the carbon utilisation of concrete:

> Concrete is currently the material most used in the construction industry, yet its high levels of consumption have also turned it into a primary contributor to the production of carbon dioxide on the planet. Researchers worldwide have hence been exploring ways to improve the fabrication of concrete, reducing its adverse effects on the environment (Fadelli, 2018, p. 1).

Fadelli noted that 3-d construction printing is, in addition to potential advantages related to cost and efficiency, a means of reducing the carbon footprint of the traditional use of concrete. Therefore, 3-d construction printing can be considered in lights of its ability to foster improved utilisation of carbon.

5.2.3 Socio-Economic Factors

Despite the threat of climate change and resource depletion, there is continuous demand for expansion of the built environment and increased productivity from the construction industry - particularly as Ronald & Dewilde (2017) point out that there is a growing gap between the demand for residential properties and supply in the Netherlands, which have socio-economic impacts on society. Boelhouwer (2017), makes the point that creating the sufficient amount of jobs needed in the construction industry before the ending of an economic cycle, is not possible and therefore the housing demand does not match with the housing supply. Currently, this miss-match is a never-ending cycle. It is suggested that on the longer term, 3-d construction printing could potentially contribute to productivity in the sector because there is less need for employees, but also less specialised jobs are needed to build housing with 3-d printing.

Finally, the construction industry plays a significant role in the national economy, contributing an estimated annual average of 10% to the economy in the Netherlands (European Commission (EC) 2016), which suggests that an efficient and productive industry is needed to ensure value for the public sums invested in the built environment (Ashworth & Hogg 2014; Myers 2016). In summary, therefore, there is a strong case for the use of innovation, sustainable and efficient technology in the construction industry and an exploration of the use of 3-d construction printing has merit.

6 Research Aim and Objectives

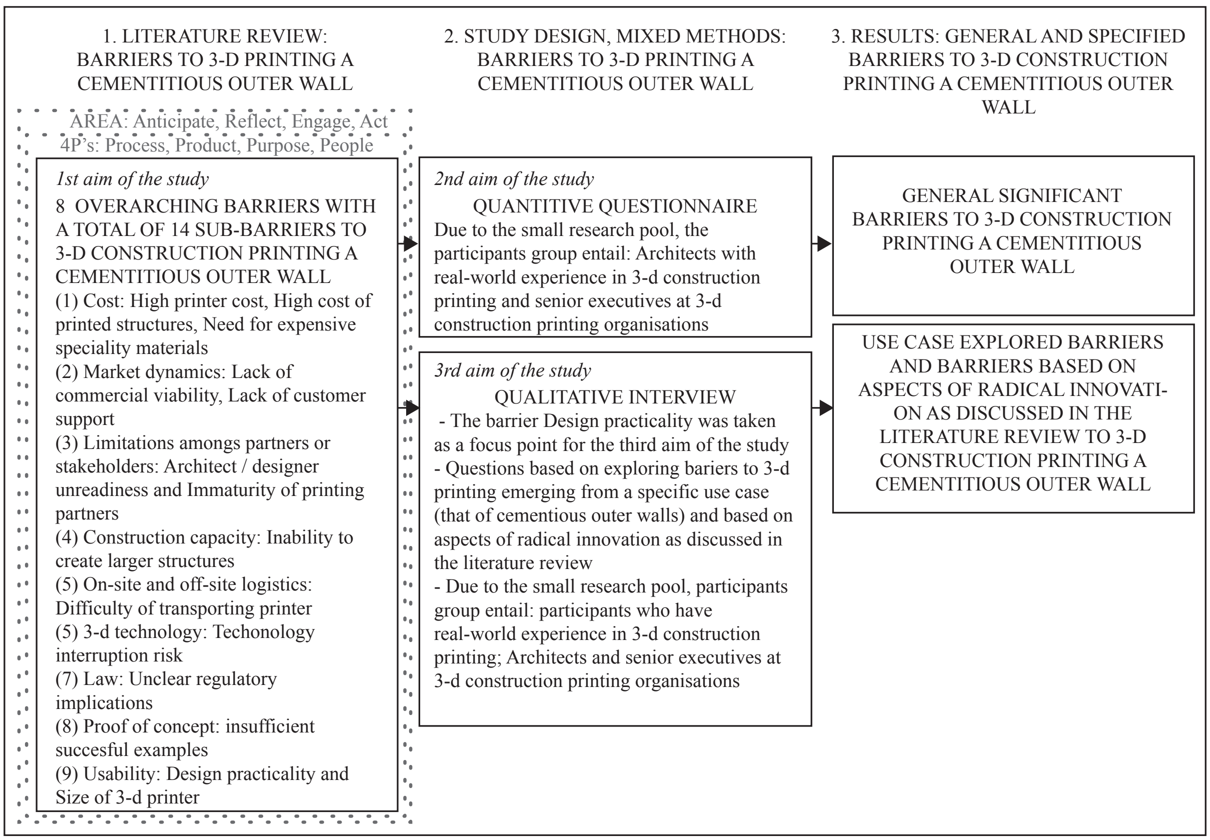


Figure 1. Framework (author)

The aims of the research were threefold (see also figure 1, Framework). The first aim of the research was to conduct a systematic review of the literature to identify the most common potential barriers to the adoption of 3-d printing in the construction industry. The second aim of the research was to execute a primary research project, based on a questionnaire, to measure the importance accorded to each of the barriers to 3-d printing identifying in the literature review. The third aim of the research was to conduct a qualitative analysis of a specific barrier in 3-d printing in construction, namely the design practicality in the 3-d printing of a cementitious wall.

The first and second aims of the research overlap substantially, whereas the third aim of the research is more independent of the other two aims. The first aim of the research consisted of a scoping search designed to identify general kinds and classes of barriers, whose importance to two construction stakeholders with real-word 3-d construction printing experience (that of senior executives of 3-d construction companies and architects) was then quantitatively tested. In this manner, the first aim of the research was to generate a list of general barriers that informed the data analysis for the second aim.

The third aim of the research was distinct. In executing the third aim, the focus of the research was on examining a specific 3-d printed product from the perspective of two stakeholders, that is, the architect with real-world 3-d construction printing experience and the 3-d construction printing manufacturer. 3-d printing in the construction industry can generate innumerable components, products, and materials that are of relevance to various stakeholders (including architects, construction companies, project managers, and clients). The first and second research aims of the study added to the limited general knowledge on 3-d printing barriers in the construction industry by approaching the subject matter as broadly as possible—that is, by not attempting to differentiate between the two different stakeholders' perspectives and by articulating general rather than specific barriers. However, the responders are asked for their 3-d construction printing experience, were then grouped afterwards by their field of expertise and experience in 3-d construction printing. The third aim of the study focused on a specific barrier, the design practicality in the 3-d printing of a cementitious outer wall component and a specific stakeholder class in order to build the specific, practical, and in-depth knowledge that could not be generated in the first and second aims of the study.

Fourteen major barriers were identified in the literature review, namely:

- High printer cost
- Immaturity of printing partners
- Unclear regulatory implications
- Inability to create larger structures

- High cost of printed structures
- Lack of commercial viability
- Lack of customer support
- Design practicality
- Size of the 3-d construction printer
- Insufficient successful examples
- Architect / designer unreadiness
- Difficulty of transporting printer
- Technology interruption risk
- Need for expensive speciality materials

It is important to note that these barriers, as well as other barriers, often refer to the same issues articulated in different ways by different researchers. Therefore, these 14 barriers cannot be considered as a final summation of all the barriers to 3-d printing in the construction industry. The 14 barriers do, however, offer a starting point, not only as a means of identifying individual barriers to 3-d printing in the construction industry but also as a means of classifying and sub-classifying these barriers into other categories.

The quantitative portion of the study consisted of a measurement of both the point estimates and statistical significant of a 6-point Likert analytical scale as applied to each of the barriers, as follows:

RQ1: Did study participants find high printer cost to be a significant barrier to the adoption of 3-d printing in the construction industry?

H10: High printer cost is not a significant barrier to the adoption of 3-d printing in the construction industry.

H1A: High printer cost is a significant barrier to the adoption of 3-d printing in the construction industry.

RQ2: Did study participants find immaturity of printing partners to be a significant barrier to the adoption of 3-d printing in the construction industry?

H20: Immaturity of printing partners is not a significant barrier to the adoption of 3-d printing in the construction industry.

H2A: Immaturity of printing partners is a significant barrier to the adoption of 3-d printing in the construction industry.

RQ3: Did study participants find unclear regulatory implications to be a significant barrier to the adoption of 3-d printing in the construction industry?

H30: Unclear regulatory implications are not a significant barrier to the adoption of 3-d printing in the construction industry.

H3A: Unclear regulatory implications are a significant barrier to the adoption of 3-d printing in the construction industry.

RQ4: Did study participants find the inability to create larger structures to be a significant barrier to the adoption of 3-d printing in the construction industry?

H40: Inability to create larger structures is not a significant barrier to the adoption of 3-d printing in the construction industry.

H4A: Inability to create larger structures is a significant barrier to the adoption of 3-d printing in the construction industry.

RQ5: Did study participants find high cost of printed structures to be a significant barrier to the adoption of 3-d printing in the construction industry?

H50: High cost of printed structures is not a significant barrier to the adoption of 3-d printing in the construction industry.

H5A: High cost of printed structures is a significant barrier to the adoption of 3-d printing in the construction industry.

RQ6: Did study participants find lack of commercial viability to be a significant barrier to the adoption of 3-d printing in the construction industry?

H60: Lack of commercial viability is not a significant barrier to the adoption of 3-d printing in the construction industry.

H6A: Lack of commercial viability is a significant barrier to the adoption of 3-d printing in the construction industry.

RQ7: Did study participants find lack of customer support to be a significant barrier to the adoption of 3-d printing in the construction industry?

H70: Lack of customer support is not a significant barrier to the adoption of 3-d printing in the construction industry.

H7A: Lack of customer support is a significant barrier to the adoption of 3-d printing in the construction industry.

RQ8: Did study participants find insufficient success examples to be a significant barrier to the adoption of 3-d printing in the construction industry?

H80: Insufficient successful examples are not a significant barrier to the adoption of 3-d printing in the construction industry.

H8A: Insufficient successful examples are a significant barrier to the adoption of 3-d printing in the construction industry.

RQ9: Did study participants find architect / designer unreadiness to be a significant barrier to the adoption of 3-d printing in the construction industry?

H90: Architect / designer unreadiness is not a significant barrier to the adoption of 3-d printing in the construction industry.

H9A: Architect / designer unreadiness is a significant barrier to the adoption of 3-d printing in the construction industry.

RQ10: Did study participants find the difficulty of transporting printers be a significant barrier to the adoption of 3-d printing in the construction industry?

H100: The difficulty of transporting printers is not a significant barrier to the adoption of 3-d printing in the construction industry.

H10A: The difficulty of transporting printers is a significant barrier to the adoption of 3-d printing in the construction industry.

RQ11: Did study participants find technology interruption risk to be a significant barrier to the adoption of 3-d printing in the construction industry?

H110: Technology interruption risk is not a significant barrier to the adoption of 3-d printing in the construction industry.

H11A: Technology interruption risk is a significant barrier to the adoption of 3-d printing in the construction industry.

RQ12: Did study participants find the need for expensive speciality materials to be a significant barrier to the adoption of 3-d printing in the construction industry?

H120: The need for expensive speciality materials is not a significant barrier to the adoption of 3-d printing in the construction industry.

H12A: The need for expensive speciality materials is a significant barrier to the adoption of 3-d printing in the construction industry.

The qualitative research questions of the study are as follows:

RQ13: From the perspective of an architect, what the envisioned barriers to the adoption of 3-d printing for the design of cementitious outer walls?

RQ14: From the perspective of an architect, how can envisioned barriers to the adoption of 3-d printing for the design of cementitious outer walls be overcome?

RQ15: From the perspective of a 3-d printing manufacturer, what the envisioned barriers to the adoption of 3-d printing for the design of cementitious outer walls?

RQ15: From the perspective of a 3-d printing manufacturer, how can envisioned barriers to the adoption of 3-d printing for the design of cementitious outer walls be overcome?

4.1 Background

This section presents the theoretical background for the research, which starts by considering the wider context of the industry by taking account of the factors which influence the use of materials on a construction project. This is then narrowed to the specific issues that directly affect waste, carbon emissions and waste in the construction process, as this provides a sound foundation on which to build the case for cementitious 3-d construction printing. The theoretical framework used to develop this research is based on that used in the Responsible research and innovation (RRI) developed as part of the EC (2017b) drive for a sustainable society (Stahl & Coeckelbergh, 2016). First and foremost, 3-d printing can be described in terms of additive manufacturing and its premises:

> Additive Manufacturing (AM), commonly known as 3-d printing, produces components by building-up structures from small deposits of materials….Comparing AM with other manufacturing processes such as formative processes, where material is deposited in a mould that has the desired shape, and subtractive processes, where a solid piece of material is cut into the desired shape, formative processes require the production of the mould to manufacture a product in mass quantities, and subtractive processes produce waste material,

> as the material being cut is not reused. AM can advantageously create a wide range of shapes without the need of a mould and only using the required material, filling a gap left by the other manufacturing processes (Camacho et al., 2017, p. 1).

Another, similar definition of 3-d printing in terms of additive manufacturing was provided by Kidwell as follows:

> 3-d printing refers to an automated additive manufacturing process in which three-dimensional objects are created by laying down successive layers of material. The process starts with the creation of a 3-d model using Computer Aided Design (CAD) software. The model is then sent to the 3-d printer as a Stereolithography Language (STL) file. From there, the model is broken down into layers that can be successively applied on top of each other to form the object (Kidwell, 2017, p. 1).

It is argued that there is merit in using additive manufacturing in the construction industry, yet Berger (2013) maintains that despite academic research supporting the use of additive manufacturing in construction, the industry is slow to adopt the technology. Koskela & Vrijhoef (2001) are unsurprised, pointing out that the construction industry has been slow to adopt new technologies, which is a key contributing factor to lower levels of productivity, quality and product functionality in the industry. This reluctance can be traced to a range of factors, including institutional factors and the fragmented nature of project delivery.

The background of 3-d printing in construction can also be considered by means of a specific example, one that is also the focus for the third research aim of the study. This example offers a means of exploring the advantages, barriers, and other characteristics of 3-d printing in a real-world construction context, one that allows specific discussions of design choices, technological issues, and the relation of 3-d printing to a genuine product. While 3-d printing is discussed in more general terms related to innovation subsequently in this study, it is also important to be able to situate 3-d printing in a real-world context, including real-world problems, barriers, alternatives, and potential solutions.

One of the most common architectural components of any building is the outer wall (Moffett, Fazio, & Wodehouse, 2003). Outer walls establish the boundaries and limits of a building and, as such, are important determinants of the overall aesthetic of the building (Kontoleon & Eumorfopoulou, 2010). However, outer walls are also important in that they provide a layer of insulation for the building. Outer walls are the first and perhaps the most important layer between the building and the elements, rendering them extremely important from a functional perspective in addition to their aesthetic importance (Moffett et al., 2003). The issue of 3-d printing barriers in construction can be considered as part of the scenario of the off-site fabrication, using additive manufacturing, or a cementitious outer wall. In this scenario, one of the guiding assumptions is that the outer wall requires insulative properties that, in the Netherlands, have to achieve an energy label of C at worst. Therefore, such a cementitious outer wall must possess insulative as well as structural properties (Moffett et al., 2003). In terms of insulation, considerations include the use of insulative additives, foam and appropriate airspaces (Zhang et al., 2014). In terms of reinforcement, considerations include the use of reinforcement additives, mesh, and rebar (Zhang et al., 2014). In the example of a cementitious outer wall, 3-d printing can be considered in two stages. First, 3-d printing can be considered in terms of advantages over traditional approaches to designing and building cementitious outer walls. Second, specific barriers to the use of 3-d printing for the creation of cementitious outer walls can be continued. This approach, in which barriers are understood in the context of adoption decisions, mirrors the structure of both the literature review in particular and the thesis in general. There are numerous advantages of 3-d printing in construction, but adoption decisions have to be considered in the larger context of identifying and overcoming specific barriers.

6.1 Innovation in the construction industry

6.1.1 What is innovation?

Innovation can be described as generating solutions that resonate with the concerns of the Zeitgeist. These solutions enable transformation within the changing context of space and time. According to Elmualim (2014) innovation is established by associative thinking, analogy and metaphor are the key drivers for innovation, so that change is slow and gradual. Innovation is mostly discovered through trial and error (Elmualim, 2014, p. 187).

According to Green et al. (2004), the understanding of innovation within construction academia is still considered to be underdeveloped and fragmented. However, innovation occurs when knowledge is shared between previously separated domains and combined in new ways (Justesen, 2004). At the same time, innovation will only occur when the combination of domains lead to successful fusion of a new product, process or service. In addition, successful exploitation and diffusion of that invention are equally important for the creation of innovation. Justesen (2004) add that innovation is the practice of creation, conversion and commercialisation.

Porter (1998) considers that innovation is one of the most pressing components of the competitive advantage of organizations. Goyal and Pitt (2007) point out that innovation is essential for the organization's survival.

The business model has become of increasing interest and importance for analysis in innovation studies. Within this domain, a consensus is arising that the role of the business model is divided. First, by allowing managers and entrepreneurs to connect innovative products and technologies to implemented output in a market, the business model represents an important vehicle for innovation. Second, the business model may also be a source of innovation in and of itself. It represents a new dimension of innovation, distinct or in other words commentary, to traditional dimensions of innovation, such as product, process and service (Dodgson et al., 2013, p. 412)

Peigneur & Osterwalder (2010) translated the business model into a scheme called the business model canvas which describes the following nine categories: (1) Value Proposition, (2) Customer Segments, (3) Channels, (4) Customer Relationships, (5) Key Activities, (6) Key Resources, (7) Key Partners, (8) Revenue Streams, (9) Cost Structures.

3-d printing is an innovation in the construction industry primarily because of its effects on processes (Bos, Wolfs, Ahmed, & Salet, 2016). By changing the manner in which structures, components, and materials are generated, by shifting these productive processes to printers, 3-d printing de-emphasises the use of labour power, allows the functions of the traditional factory to be carried out anywhere a 3-d printer can be situated. In this sense, 3-d printing affects each of the 9 categories listed by Peigneur & Osterwalder (2010), that is, (1) Value Proposition, (2) Customer Segments, (3) Channels, (4) Customer Relationships, (5) Key Activities, (6) Key Resources, (7) Key Partners, (8) Revenue Streams, (9) Cost Structures. In diagram 1, the suggested potential changes in the Business model canvas to 3-d construction printing can be found.

Category	Suggested potential changes
Value Proposition	A shift in performance, customisation, controllability, risk reduction and usability
Customer Segments	Shift to a multi-sided platform

Channels	Shift or elimination of channels
Customer Relationships	Re-established partnerships
Key Activities	Different design processes
Resources	A shift in materials, shift in personnel from human labour to automation
Key Partners	Shift or elimination of Key Partners
Revenue Streams	A shift in revenue streams
Costs Structures	The shifts in costs and value

Table 1: Suggested potential changes in the Business model canvas to 3-d construction printing (Peigneur & Osterwalder, 2010; author)

In the domain of 3-d printing, Neudecker et al. (2016) pointed out that sprayed concrete technology was invented in Germany in 1919, by the engineer Carl Weber. Weber's company, Torkret, pioneered what is known as shotcrete, that is, "a concrete which is conveyed in a closed tube line to a nozzle, from where it is pneumatically sprayed onto a surface and compressed by the impact energy" (Neudecker et al., 2016, p. 334). On the basis of their discussion of shotcrete, Neudecker et al. argued that elements of 3-d printing technology could be dated to the 1920s. However, in terms of innovation, Neudecker et al. argued that innovation in the domain of 3-d printing is based not only on isolated technological components such as shotcrete but also, and more importantly, on "networking of production techniques, the so-called ‘smart factory,' and human-robot cooperation" (Neudecker et al., 2016, p. 333). For Neudecker et al., innovation is therefore defined as the combination of novel technological elements (such as shotcrete and other precursors and examples of hardware innovation related to 3-d printing technology) with novel developments in robotics, software, and automated processes.

Neudecker et al.'s (2016) description and definition of innovation in the context of 3-d printing can be expanded upon in light of Salet's (2018) discussion of a 3-d printing project that took place in the Netherlands in 2018. Like Neudecker et al., Salet pointed out that defining innovation concerning 3-d printing should be based not merely on an identification of novel technology but also on the kinds of automation and computing processes underlying the project. However, Salet also called attention to 3-d printing innovation specifically based on hardware innovations. Salet reported on a 3-d printing project in which printed reinforced and prestressed concrete was utilised to erect a cycling bridge in Gemert. In this context, Salet stated that "the printer head was supplemented with a ‘reinforcement entraining device' (RED) that allows the introduction of a reinforcement medium (metal cable) to the concrete filament…. meeting the demands of both structural behaviour and aesthetics" (Salet, 2018, p. 4-5).

Thus, when referring to innovation in the domain of 3-d printing for construction, attention must be paid to how innovation is defined. Innovation can be highly specific and based on particular components of technology, as in the experimental construction discussed by Salet (2018). However, innovation can also be based on the underlying process and computing elements noted by Neudecker et al. (2018).

Holzl and Janger (2011) defined innovation in terms of technology as well as non-technological factors. Holzl and Janger noted that "We define all firms that introduced a new or significantly improved product or process and/or have ongoing innovation projects as innovators…we distinguish two types of innovators: R&D innovators is the set of innovative firms, that perform own R&D. The set of innovators that do not perform their own R&D is called non-technological innovators" (Holzl & Janger, 2011, p. 9). Holzl and Janger's definition of innovation is somewhat reminiscent of that provided by Neudecker et al. (2016), who differentiated the technological / hardware innovations in 3-d printing from innovations related to processes and other factors outside the domain of technology.

6.1.2 Scalability

According to Nielsen et al. (2018), besides the importance of business model innovation, real successful businesses know how to position themselves in the “hot zone” of business model scalability. This is considered even more critical than the increasingly hot topic of business model innovation. Exponential returns to scale mostly erect in business models where capabilities, new resources, or value propositions bring completely new premises to an existing industry. Scalability aims to achieve profitable growth and is considered as a fundamental consideration for investors and executives. If executives are incompetent in implementing scalability themes into their business model design, they risk being left behind. Amazon.com Inc. is an example of how they overshadowed the book industry by being highly scalable. The term scalability is often used to identify where there is a good possibility for changes in size or volume. It refers to a system’s ability to expand output on demand when resources are added. Coupling scalability to business models accommodates a framework to consider and asses business potential. Another essential aspect of scalability is that a 3-d construction organization has sufficient flexibility to grow while incorporating the effects of external stresses, for instance, new competition, macroeconomic pressure of regulatory alterations. Nielsen et al. (2018) identified five aspects on how organizations can achieve scalability: (1) adding new distribution channels, (2) liberate the business from traditional capacity constraints, (3) outsourcing capital investments to partners who effectively became participants in the business model, (4) to have customers and other partners play multiple roles in the business model, (5) to create platform models where competitors may become customers. Coutu (2014) adds to this that early-stage companies are missing the will and ambition to scale. Therefore, they need to (1) commit to growth and create realistic growth targets and develop a way forward. When this ambition for growth is there, (2) a broad management skill set is required and useful mentorship.

Moreover, it is also of importance that (3) standardized processes are created, (4) core competencies are identified and (5) the articulation of competitive strength is thoroughly considered. Stampfl et al. (2013) proposed an earlier model of an explorative model of a business model (see figure 2). This explorative model has similarities to Nielsen et al. (2018) and Coutu (2014) and is considered interesting on a contextual level.

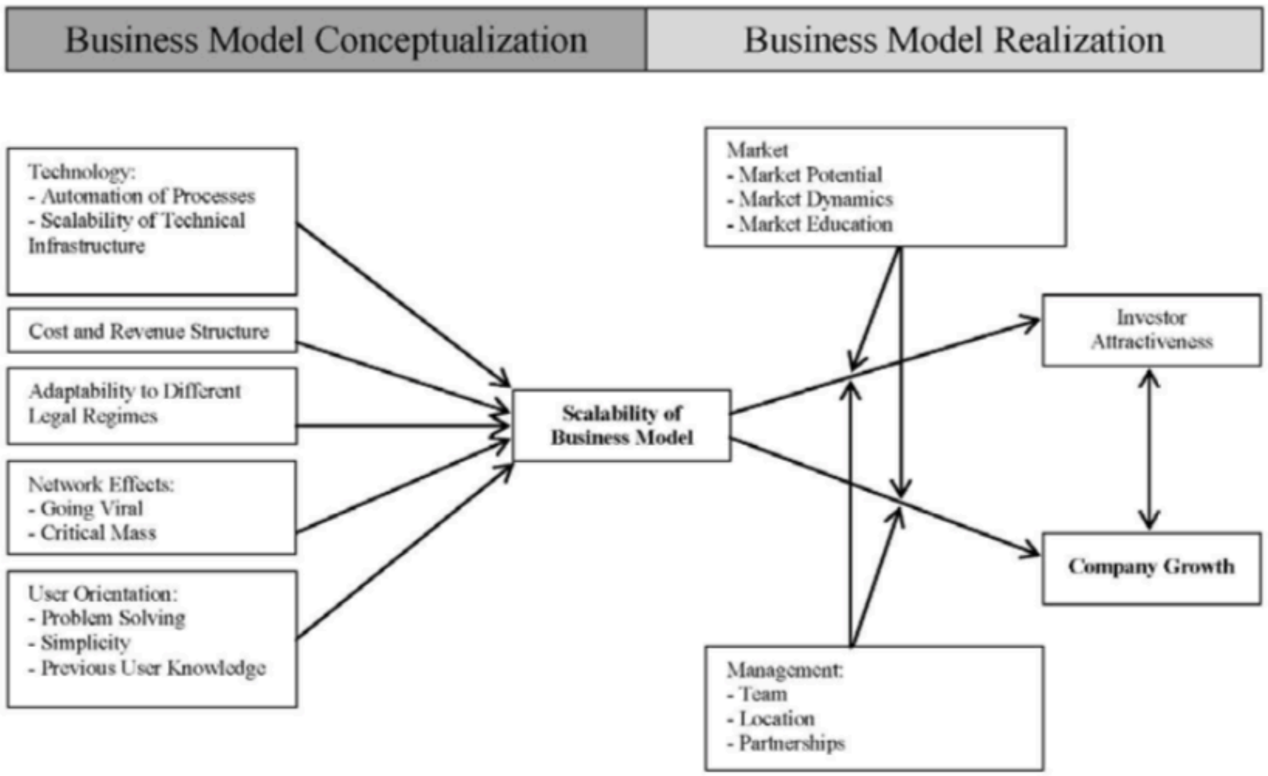


Figure 2. Explorative model of business model scalability (Stampfl et al., 2013).

6.1.3 Understanding Disruptive Technology

Most new technologies cultivate improved product performance. Clayton & Christensen (1997) call these sustaining technologies. Some sustaining technologies can be discontinuous or extreme in character, while others are of an incremental nature. Sustaining technologies have one thing in common; they improve the performance of established products, along the dimensions of performance that mainstream customers in large-scale markets have historically valued. Clayton & Christensen (1997) point out that the most technological advances in a given industry are sustaining in character. Another important finding revealed by Clayton & Christensen (1997), is that rarely even the most radically difficult sustaining technologies provoke the failure of leading firms.

From time to time, however, disruptive technologies arise; innovations that result in worse product performance, at least on the shorter term. Ironically, it was found that disruptive technology brought the leading firms to its knees (Clayton & Christensen, 1997).

Disruptive technologies have a very different value proposition than had been available previously for a certain market. Generally, established products outperform disruptive technologies in mainstream markets. But disruptive technologies have other features that of a marginal (and commonly new) customers value. Products which has its basis in disruptive technologies are typically simpler, cheaper, smaller, and, frequently, more convenient to use (Clayton & Christensen, 1997).

3-d printing technology disrupts the construction industry in several ways. First, 3-d printing is simpler than typical productive methods in construction, as the 3-d printer is designed to replicate certain complexities in material design; the need for productive knowledge is thereby reduced (Hager, Golonka, & Putanowicz, 2016).

Boelhouwer (2017) makes the point, that creating the sufficient amount of jobs needed in the construction industry before the ending of an economic cycle, is not possible in the Netherlands and therefore the housing demand does not match with the housing supply. Unemployment decreased rapidly in the construction industry during the last financial crisis. A decrease of 80,000 jobs between 2008-2013, and the number of bankruptcies was extremely high. Therefore, it is difficult to find construction workers in general. Moreover, it is hard to create these jobs again before another crisis hits. This will eventually, result in a shortage of housing and cause another housing crisis (Boelhouwer, 2017; Cobouw.nl, 2019). On the longer term, 3-d printing could potentially contribute to productivity in the sector because there is less need for employees, but also less specialised jobs are needed to build housing with 3-d printing. On the shorter term, the main advantage of 3-d printing is the fabrication of unique complex elements, facilitates mass customisation, the possibility of late alterations and integrated connections (Despeisse et al., 2017). It is suggested, when 3-d construction printing can deliver on its promises, it will disrupt the built environment on these shorter and longer term issues.

Second, there is some evidence that 3-d printing is cheaper than traditional approaches, although the value proposition of 3-d printing is likely to be different for different companies and has to be appreciated in the context of a somewhat complicated cost-benefit analysis that will depend on the dynamics of specific construction companies and their undertaken projects (Hager et al., 2016). Third, the convenience of 3-d printing appears undeniable, as it is based on the use of a printer exchanged for other productive assets that have to be housed in fixed locations, as fixed assets, with the cooperation of many kinds of labour and management to unlock their value (Hager et al., 2016).

Some relevant examples of disruptive technology were given by de Jong, Marston, Roth, and van Biljon (2013) as follows:

> Recall the airline industry before the emergence of low-cost carriers: a decade ago, it was hard to imagine travellers making multiple connections on a journey in exchange for a substantially lower fare. Similarly, no one had heard of an enterprise IT manager "renting" core applications from a company on the other side of the globe, or of consumers carrying mobile devices with today's plethora of functionalities. Today, we don't think twice about using the point-to-point networks that dominate air travel; on-demand, pay-as-you-go "cloud" services; and smartphones with a multiplicity of apps (Marston et al., 2013, p. 3).

In this definition, disruptive technology is described not merely in terms of novel technology but in terms of how the practical applications of technology alter industries and customer experiences. Bos et al. (2016) suggested that disruptive innovation attributable to 3-d printing in the construction industry could take the following forms: (a) Radical improvements in the production of on-site construction materials, (b) radical improvements in the production of off-site construction materials, and (c) radical improvements in the ability to move off-site construction processes to on-site construction processes.

The aforementioned aspects of innovation are highly general insofar as they address 3-d printing as a general practice. However, understanding the innovativeness and disruptive capability of 3-d printing requires more specific examples of the benefits of 3-d printing in the construction industry. Such examples can be given in the context of cementitious materials, and, in keeping with the focus of the qualitative research questions of the study, with cementitious outer walls.

First, it should be noted that conventional castings for cementitious materials are expensive to make and can also leak. The cost and manufacturing variability of conventional castings for cementitious materials can both be better controlled by the use of 3-d printing. 3-d printing can print castings with foam, metal mesh, FLAM (fungal-like adhesive material), or dynamic casting, for example (Sanandiya et al., 2018; Zhang et al., 2014). Traditionally, wood is used as a reinforcement material, but the addition of FLAM and its incorporating through a 3-d printing process would represent an innovation to the status quo (Sanandiya et al., 2018).

6.1.4 Innovators dilemma

Clayton & Christensen (1997) have designed a framework which explains why sound decision making by great managers can lead organisations to failure. The picture the authors paint is truly that of an innovator's dilemma; the logical, competent decision making of management that are critical to the success of their companies are also the reasons why they lose their positions of leadership.

Building on the understanding of why and under what circumstances new technologies have caused great firms to fail, Clayton & Christensen (1997) prescribe managerial solutions to the dilemma—how executives can simultaneously do what is necessary for the near-term health of their businesses, while focusing the right resources on the disruptive technologies that someday could lead to their downfall.

It is suggested that 3-d printing could be a disruptive technology and that the innovator's dilemma might apply to the construction industry. In essence, the innovator's dilemma posed by the 3-d printing applications for construction is that the pioneers in this field will bear the expenses and other risks of facilitating the technological maturity of 3-d printing; once technology maturity has been achieved, then other, larger companies can enter the field and dominate it (Xia & Sanjayan, 2016). This dilemma applies primarily to technology companies that are in the field of 3-d printer design, manufacture, and related information technology (IT), not to construction companies, architecture firms and other end users who are only users of 3-d technology for construction purposes. However, the failing of a construction firm or an architecture firm is suggested in simply not matching with the needs of the client. For example, currently, there are still a lot of construction companies and architecture firms that do not work with IT-related programs, such as Autodesk's BIM or Revit design program. These programs such as BIM gain traction, but the firms who will lack in efforts on investing in these innovations, however, will risk the opportunity to missing out on obtaining a commission to design or build a building for clients who expect that their partners have the same IT-related interests (Papadonikolaki, 2017). It is suggested that on the longer term, this is also the case with 3-d construction printing, especially when margins are low.

One point made by Clayton and Christensen (1997) is that innovations are often themselves composed of combinations of elements that are not individually innovative. In the case of portable digital music players, for example, the separate elements of this innovation—that is, Flash drives, a small-electronics user interface, and MP3 encoding—all pre-existed the debut of digital music players such as the Apple iPod. The same principle appears to apply to 3-d printing as an example of innovation. For example, in the context of the design and construction of a cementitious outer wall (which is the scenario for the qualitative research questions of this study), 3-d printing, both 3-d printing and FLAM exist, but their combination can be described as innovative (Sanandiya et al., 2018).

In the way, Fernandez (2019) describes FLAM, it is suggested that this material could be an interesting extrusion material for 3-d construction printing (insulative lost-) formwork to make a cementitious outer wall:

> FLAM, a fully biodegradable and ecologically sustainable material that is made from cellulose and chitin, the two most common natural polymers and industrial byproducts on Earth. The cost of FLAM is less than 2$/kg, similar to commodity plastics and is 10 times lower than the cost of common filaments for 3-d printing. This material can also be used to 3-d print large structures (Fernandez, 2019, P.1).

The incorporation of FLAM into a 3-d printing approach to a cementitious outer wall is, first, an innovation in terms of design freedom, an element of innovation that can be related to Clayton and Christensen's (1997) discussion of innovation and disruption. In terms of such innovations as digital music players and video cassette recorders, consumers already had access to music and movies, but with limited freedom. For example, both tape and video cassette recorders had highly limited storage space and presented a cumbersome mechanism for scrolling through, or toggling between, content (Norman & Verganti, 2013). In terms of 3-d printing, the technology affords architects more design freedom. Higher design freedom is an innovation in itself, if understood from the perspective of the user in the manner described by Clayton and Christensen.

FLAM's incorporation into a 3-d printed cementitious outer wall requires an open structure to dry the material with heated air. Afterwards, the cementitious outer wall needs to be plastered with FLAM and sanded, suggesting the importance of value-added on- or off-site processes that come after the 3-d printing itself (Sanandiya et al., 2018). The combination of FLAM and 3-d printing represents thus an innovation in manufacturing as well as design processes.

The combination of FLAM and 3-d printing is only one of several examples of disruptive innovation that follow the same pattern. This pattern is the combination of the technology of 3-d printing technology with specific materials, in specific construction contexts, to solve specific problems (including problems related to cost, design, complexity, and function). As such, it would be fallacious to consider 3-d construction printing on its own as a disruptive innovation. Rather, the phrase *3-d construction printing* should be understood to convey some combination of products (including not only 3-d printers themselves but the materials on which they operate), data, production processes, designs, and business processes. For this reason, any discussion of 3-d printing as a disruptive innovation is bound to be more complex than Clayton and Christensen's (1997) discussion of disruptive innovation, which is based on discrete products rather than on a combination of products, materials, processes, data, and business arrangements.

For example, a digital music player is an innovation that is encapsulated in a single product (Norman & Verganti, 2013). 3-d printing was an innovation of this kind when 3-d printers were first introduced into the global marketplace in 1992, building on research, scholarship, and patents from the 1980s (van Wijk & van Wijk, 2015). In this context, it can be noted that 3-d printing is, as a commercial product, roughly as old as the World Wide Web (van Wijk & van Wijk, 2015). For this reason, it would be unreasonable to describe 3-d printers—whether understood as commercial products or in terms of earlier intellectual property—as innovations, much less disruptive innovations. The innovativeness of 3-d printing can be better understood in terms of either (a) improvements to the underlying technology that are substantial enough to be considered as innovations in their own right; or (b) novel combinations of products, data, production processes, designs, and business processes. These two types of innovation (and, possibly, disruptive innovation) related to 3-d printing in the construction industry can be understood as manifestations of incremental and radical innovation, respectively. According to Leifer et al., the distinction between these two kinds of innovation is as follows:

> Incremental innovation, usually emphasises cost or feature improvements in existing products or services and is dependent on *exploitation* competencies. In contrast, Radical change concerns the development of new businesses or product lines based on new ideas or technologies or substantial cost reductions . . . That transform the economics of a company and therefore require *exploration* competencies. (Leifer et al., 2000, p. 5).

Both incremental innovation and radical innovation have been discussed in the literature review, and the barriers to 3-d printing adoption in the construction industry can also be considered in light of these two types of innovation. From the perspective of the construction industry itself, an example of incremental innovation utilising 3-d printing could be the replacement of traditionally designed and produced cementitious outer walls with 3-d printed equivalents. An example of a radical innovation related to the use of 3-d printing technology in the construction industry could be the combination of (a) 3-d oriented cementitious outer walls incorporating FLAM or some other material that has rarely been integrated into 3-d printing, (b) the leveraging of 3-d printing to move production on-site, and (c) the leveraging of 3-d printing to remove some construction companies from the existing supply chain. In this example, what constitutes radical innovation in the context of 3-d printing is a novel combination of products, data, production processes, designs, and business processes.

A practical example of radical innovation in the context of 3-d printing can be derived from Gramazio and Kohler's cross-functional robotics, technology, and architectural laboratory in terms of a mesh mould research project:

> The research project Mesh Mould investigates the unification of reinforcement and formwork into a single robotically fabricated material system. During the first research phase, a spatial robotic extrusion process was developed, allowing the examination of the relationship between mesh typology and rheological behaviour of concrete. The second research phase at the National Competence Centre in Research (NCCR) Digital Fabrication focuses on the translation of the structurally insufficient polymer-based extrusion process into a fully load-bearing construction system (Gramazio & Kohler, 2018, p. 1).

In his example, the radical innovation is the application of a 3-d printing system to a new form of automation, experimental interaction with concrete, and development of a new construction system. The individual components of Gramazio and Kohler's project are neither incrementally nor radically innovative, insofar as robotics, 3-d printing, the analysis of cementitious properties, and the design of new construction systems already exist. The element of radical innovation, and the suitedness of Gramazio and Kohler's mesh mould research to Clayton and Christensen's (1997) disruptive innovation framework, emerges from the novel combination of the various components of this project.

6.1.4.1 Reason for established companies to not implement a disruptive technology

Clayton & Christensen (1997) conclude that established companies do not invest heavily in disruptive technologies because it is not a rational financial decision for them to make. This way of reasoning is embedded in three bases. First, disruptive products are simpler and lower-priced; they generally promise lower margins, not greater profits. Second, disruptive technologies commonly are first commercialised in emerging or irrelevant markets. And thirdly, leading firms' most profitable customers generally do not want, and indeed at the beginning can't use, products based on disruptive technologies. Generally, in the first instance, a disruptive technology is embraced by the least profitable customers in a market. In this case it is suggested, architecture firms are the ones who want an innovative design, but for them it does not makes sense to develop new ways of production methods. Although they could have high budgets for a certain innovative project, it does not make sense for them nor a technological company, to develop an expensive robotic product such as a robotic 3-d printer, solely for a tiny niche; freeform architecture. Finding the right partners to develop a 3-d construction printer is key to develop a product that the first (niche) customers want to use. Moreover, objections for the practical use of a 3-d construction printer, thus the potential disruptive technology, are currently the size and the bulkiness of the robot (Buchli, 2019). A 3-d printer that has the size and weight of a washing machine and is resistant to endure some beating would be better but currently does not exist.

6.1.5 Purpose of innovation

The issues the construction industry currently deals with gives purpose to innovating the construction industry. The purpose of innovation is hereafter called 'innovative purpose'. The purpose of innovating the construction industry can broadly be classified in improving its environmental sustainability and improving sustainability by meeting socio-economic demands and being profitable at the same time.

The first innovative purpose is to improve environmental sustainability in the construction industry. As previously mentioned, the construction industry in the Netherlands accounts for 19% of transport in the country and 37% of all waste generated (Dijkstra, 2016). The industry is also responsible for consuming over 4.5% of the total energy consumed in the Netherlands.

It is argued that drivers for improving the sustainability of the construction industry are, among other drivers such as changing market demands, legislation & regulation coming from the EU.

Legislation and regulation of factors such as waste, carbon emissions and waste reduction processes in the Netherlands are closely aligned with EU regulations and international commitment to reducing the impacts of climate change. The targets set by the EU include a 20% cut in greenhouse gas emissions (compared to 1990 levels) and a 20% improvement in energy efficiency (EC 2017a). The World Bank (2016) indicates that carbon emission reductions need to be addressed through a multitude of overlapping initiatives, including carbon pricing with the IPCC (2013), implying that the construction industry must play a role in reducing its carbon footprint. It is argued that this requires greater use of technology and innovation in the construction industry, to reduce the carbon footprint of the built environment to comply with European Union (EU) and global commitments. Radical reductions in carbon emissions require better control of all industrial sectors, including the construction industry. On national level, it is expected that newly build housing have at least an energy C label.

The second innovative purpose is improving sustainability by meeting socio-economical demands. As mentioned in the introduction, the industry consumes large volumes of public investment; as such, it is essential that the industry is productive and efficient. As Ronald & Dewilde (2017) point out, there is a growing gap between the demand for residential properties and supply in the Netherlands, which has socio-economic impacts on society. Berger (2016) makes a practical point, suggesting that 30% of a construction worker's working time is focused on their principal activity, with the remaining 70% taken up by transporting materials, cleaning up, and looking for materials and equipment. The efficiency in the construction industry needs to increase, and the costs need to be reduced to meet the changing market demands such as to fulfil the demand for affordable high-quality housing. Elmualim (2014), describes that a fundamental issue in the construction industry is the separation of design from the project process which results in poor building performance in terms of flexibility in use, operating and maintenance costs and sustainability (Elmualim, 2014, p. 187). Boelhouwer (2017), makes the point that creating the sufficient amount of jobs needed in the construction industry before the ending of an economic cycle, is not possible and therefore the housing demand does not match with the housing supply.

According to Barbosa et al. (2017), there are seven ways to improve the efficiency of the construction industry: Reshape regulation and raise transparency, Rewire the contractual framework, Rethink design and engineering processes, Improve procurement and supply-chain management, Improve on-site execution, Infuse digital technology, New materials and advanced automation, and Reskill the workforce. It is suggested in this thesis, that the combination of (a) 3-d oriented cementitious outer walls incorporating FLAM or some other material that has rarely been integrated into 3-d printing, could have a positive impact on these seven topics.

In short, the academic literature on the subject expresses a dire need for sustainable and at the same time economically interesting developments in the construction industry, which provides for the social and economic needs of society whilst preserving the natural environment and being profitable at the same time (Kibert 2016; Nalewaik and Venters 2008). It is suggested that the combination of (a) 3-d oriented cementitious outer walls incorporating FLAM or some other material that has rarely been integrated into 3-d printing, can have a positive contribution to the innovative purposes.

6.2 Innovation in the Dutch Built Environment

Innovation is driven by behaviour, business models, regulation and legislation (Ashby, 2015). In the previous section, the innovative purpose is discussed, in other words, why the industry should innovate. In this section, the main topics for innovating the Dutch built environment will be discussed, in other words, how can the industry innovate.

Innovation in the Dutch built environment is limited by the nature of the project structure for creating buildings. In the project structure, there is an intrinsic disincentive for any particular party to bear the cost of innovation, as all parties, not merely the investing party, are likely to benefit from the innovation (Kulatunga, 2006). From this perspective, the project structure of construction creates either a moral hazard or a free rider problem that impedes innovation. Another barrier to innovation in the Dutch built environment is the lack of incentive for a contractor to take on the added risk that is associated with a desire for innovation. In a low-risk environment, there is an incentive for contractors to suppress rather than to pursue innovation (Kulatunga, 2006).

6.2.1 Offsite Manufacturing and Modular building

As previously mentioned, 3-d printing is essentially a form of off-site manufacturing which includes modular building. The benefits of this form of construction compared to a conventional building is that the bulk of the work is carried out in factory controlled conditions, resulting in a better-quality finish that reduces air permeability in the building fabric and promotes the efficient use of energy. Furthermore, the use of off-site manufacturing reduces the time of construction, with knock-on benefits for site safety and it does not rely on skilled construction workers (Lawson et al., 2014; Arashpour et al., 2017). Dijkstra (2016) makes the point that transporting materials to conventional build construction sites accounts for high levels of carbon emissions. It is suggested that the use of off-site manufacturing technology could reduce transport requirements because there is less need to transport machinery or employees to a construction site compared to a factory. Therefore, it can improve the carbon footprint of the construction project and the overall industry (Quale et al., 2012).

6.2.2 Logistics

The delivery of a construction project essentially relies on resource management, whereby in traditional construction, products are manufactured off-site and delivered to site for construction. This means that the sustainability of the construction process can be reliant on the efficiency of the resource manager, ordering the correct volume and type of materials to arrive on site when needed. It is also dependent on the correct storage of materials on site (Harris & McCaffer, 2013). Logistically, this can be challenging due to the extensive supply chain in a construction project and typically relies on the efficiency of the project manager, the relationship between the different suppliers and the accuracy of the design (Gosling et al., 2015). Čuš-Babič et al., (2014) argue that logistics can be improved by industrialising the construction process, from which it is inferred that adopting off-site technology such as 3-d printing could improve the flow of materials and information and enhance the sustainability of the construction process, thus increasing the industry's contribution to the circular economy. This would require a revamp of the traditional business model in the construction industry, and it would also require a behavioural change, which can be driven in part by legislation and regulation, but also requires a commitment to change and greater efficiency from within the industry (Ashby, 2015; Dijkstra, 2016).

Berger (2016) makes a practical point, suggesting that 30% of a construction worker's working time is focused on their principal activity, with the remaining 70% taken up by transporting materials, cleaning up, and looking for materials and equipment. It is therefore suggested that innovative technology that streamlines the supply of resources makes the construction process more efficient and productive, shortening construction time, improving profitability and reducing the environmental impact of the industry (Vrijhoef, 2015).

6.3 RRI Framework

Given the potential value of 3-d printing to the construction industry in terms of carbon reductions and sustainability (Dijkstra 2016; Yossef & Chen, 2015), it is suggested that the industry requires wider support. The EC (2017b) operate a Responsible research and innovation (IRR) fund to support innovative technology to align both the research and development process and the implementation and value of innovation. It is suggested that this initiation recognises that innovative technology can have a positive impact on an industry and at the same time create job opportunities and improve the economy whilst making organisations more competitive in the global market and securing valuable resources such as fuel. The EC (2017b) also recognise the fact that innovation is a key requirement in the fight against global warming and can lead to smarter solutions to traditional problems. Stahl & Coeckelbergh (2016, p.156) point out that research into innovative technology can be aligned with the RRI framework, which has been adopted for this thesis, focusing on the acronym AREA, which stands for:

- Anticipate — which entails describing and analysing the impacts that might arise from using the technology compared to the do-nothing case, which in this instance is retaining conventional methods of construction
- Reflect — reflecting on the need and motivations for the innovation, and the potential implications of this technology
- Engage —questioning to broaden deliberation, dialogue and engagement, which in this instance requires engagement with the industry, in this case 3-d construction printing manufacturers and architects with real-world experience in 3-d construction printing, to review the technology on its barriers
- Act — using these processes to develop a way forward for the construction industry, devising ways to influence the direction and course of the innovation process within the industry.

It is suggested that the above provides a broad framework for the study, which, as indicated by Stahl & Coeckelbergh (2016, p.156), can be focused by concentrating on the 4P's, namely:

- Process: which involves conducting research to understand additive manufacturing and 3-d construction printing in terms of its barriers compared to conventional manufacturing.

- Product: which involves assessing the consequences of use of this technology in the construction process, including cost, time and environmental impacts, waste and carbon emissions.
- Purpose: underpinning the research with clear objectives on the basis that the construction industry needs to be more environmentally and economically sustainable while being profitable and cementitious 3-d construction printing is a solution.
- People: which involves considering the construction industry's response to the technology as a key factor in achieving a more sustainable economy and in acceptance of new technology in a traditional industry.

This strategy starts with developing research on 3-d construction printing in the form of a detailed review of the current literature.

6.4 Define 3-d printing and its application in the construction industry

The standard definition of 3-d printing technology is "a process of joining materials to make objects from 3-d model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" (ASTM, 2012, p.1). This means that 3-d printing is the fabrication of objects/products, layer by layer, in either a continuous or incremental manner, facilitating the creation of a three-dimensional object on demand (Petrovic et al., 2011). According to Guo & Leu (2013), there are different forms of this technology, including material extrusion, vat photo-polymerisation, powder bed fusion, and material jetting along with binder jetting, directed energy deposition and sheet lamination (Guo and Leu, 2013; BSR, 2015). This technology can be used with a wide range of materials and is increasingly being used in a variety of industries, including the aerospace, automotive and construction industries (Despeisse et al., 2017).

Although there are different printing techniques available, the workflow is similar; each requires digital design, the 3-d printing technology and the material, where the digital design provides the instructions for the 3-d printer in the form of a 3-d modelling program (Hager et al., 2016). The file is uploaded to the 3-d printer, which slices the object being produced into horizontal layers using a command file which directs the entire process (Van Wijk & van Wijk, 2015). Van Wijk & van Wijk (2015) explains that there are different variations within these classes, including:

- Extrusion, which is a process whereby molten materials such as plastic, silicon or cement are extruded and become solid after emerging from the printer. The product is developed layer by layer until completion

- direct energy deposition, used to produce metal objects using a high-energy power source such as an electron beam or a laser to melt wire or powder to form an object

- solidification of powder, which is a powder-based printing technique based on fusing or sintering powders. Typical techniques include Selective Laser Sintering and 3-d printing

- photopolymerization uses UV-light and 3-d printing technology to develop a product layer by layer using liquid photo-curable resins. This technique includes Stereo-Lithography and the Polyjet process

- sheet Lamination builds a product by trimming sheets of materials and binding these layers using adhesive-coated paper

As explained in the research problem section, the focus of this thesis is delimited to the building of cementitious outer walls using an extrusion 3-d printer. However, this does not mean that the research is delimited to cementitious materials only. Other materials can also be used as a form of casting to create a cementitious outer wall. For example, casting of 3-d printed material to poor a cementitious material in, in combination with integrated reinforcement to build an outer wall. Suggested materials for 3-d printed castings are for example foam and FLAM (Keating et al., 2019; Sanandiya et al., 2018).

When focussing on the potential cementitious 3-d printing wall applications versus the broader drivers and barriers to 3-d construction printing, it is suggested that the FLAM 3-d printer was most interesting printer to focus on for this research (see table 2). The Eggshell research project of Gramazio Kohler Research is like the FLAM 3-d printer promising. Both techniques use 3-d-printing material to create castings and have the best scoring. However, there is no publication of the Eggshell research until 2022, and therefore the FLAM 3-d printer was suggested for the second part of the research (Gramazio Kohler Research, 2019; Sanandiya et al., 2018).

In table 3, six potential cementitious 3-d printing wall typologies are suggested. Also, their description and the name of the 3-d printer (projects) are described. In the illustration, per typology, a simplified cross-section of a 3-d printed wall element is shown. The walls can be curved to some degree, depending on the capabilities of the 3-d printer. The six typologies offer a starting point, as a means of identifying potential typologies to 3-d printing cementitious outer walls in the construction industry and secondly identifying the incompleteness and barriers in design practicality.

It is suggested that all the 3-d printers, except for the Bati3-d 3-d printer, miss the right insulative capabilities for at least a C-label. To resolve this challenge, it is suggested that the most practical solution to date, is the using of external wall insulation panels. These kinds of panels are flexible to a certain degree, which is needed when a curved 3-d printed wall is desired. Moreover, the panels have sufficient insulative capabilities (4,5 m2 K/W required). The primary use-case for these insulation panels is currently the renovation of buildings for CO2 reduction purposes. However, there is a lot of interest in the façade renovation field and might also be of use in the area of 3-d construction printing (Azcarate-Aguerre et al., 2017). Therefore, it is suggested, better insulation panels are anticipated, which can be used as an off-the-shelf product to insulate a 3-d printed outer wall. Moreover, considering the recycling process of a 3-d printed outer wall in combination with separate insulation panels; the different materials can easily be separated. For example, this does not seem to be the case for the Bati3-d 3-d printer because of the insulative lost formwork is fused to the cementitious material and is hard to separate when the building needs to be recycled. When it comes to the 3-d printing of a sustainable outer wall with high insulative capabilities in the near future, it is suggested that the ideal design solution, is an integrated solution. This means, it is suggested that the insulation can be easily separated in the recycling process but at the same time is included in the 3-d printing process and is not merely an add-on to the 3-d printed cementitious wall.

Delivery of the research	Extrusion 3-d printer applications	Manufacturer	Extruded Material	Outer wall fabrication	In situ fab.	Drivers			Barriers											
						Produtivity	Design freedom	Sustainability	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12
2022	Eggshell	ETH Zurich	Plastic	Casting for structurally		++	++	+	x	x			x	x	x	x	x	x	x	x
2019	MX3D Bridge	MX3D	Stainless steel	Deposition process of metal that solidifies		-	++	+	x	x	x		x	x	x	x	x	x	x	x
2019	Thin Folded Concrete Members	ETH Zurich	Cementitious	Direct wall extrustion	x	++	+	+	x	x	x			x	x	x	x	x	x	x
2021	Apis cor	Apis Cor	Cementitious	Direct wall extrustion	x	+	+-	+	x	x	x		x	x	x	x	x	x	x	x
2017	Mesh Mould and In Situ Fabricator	ETH Zurich	Metal casting	Mesh Casting	x	+-	+	+	x	x	x		x	x	x	x	x	x	x	x
2019	3DCP	Tech. University of	Cementitious	Direct wall extrustion		+	+-	+	x	x	x		x	x	x	x	x	x	x	
2018	Batiprint3D 3-d printer	Batiprint3D	Foam, Cementitious material, steel reinforcement	Direct foam wall extrusion, steel reinforcement, and the pooring of concrete manually into the foam casting	x	+	+	+	x	x	x		x	x	x	x	x	x	x	
2018	FLAM 3-d printer	Singapore University of Technology and Design	Fungus-Like Adhesive Material	Casting for objects such as a wall		+	++	++		x				x	x		x		x	
2017	Digital Construction Platfrom (DCP)	Mediated Matter—MIT	Foam or concrete	Direct wall extrustion	x	+	+	+	x	x	x			x	x	x	x		x	
2018	WASP 3-d	WASP	Cementitious	Direct wall	x	+	+	+	x	x	x			x	x	x	x	x	x	
2016	Shotcrete 3-d printing	Braunschweig University of Technology	Cementitious	Direct wall spraying in form of shotcrete	x	+-	++	+	x	x	x		x	x	x	x	x	x	x	x
2016	3-d Printed Bridge	Architecture of Catalonia	Reinforced concrete	Direct extrustion of a walking		+	+	+	x	x	x			x	x	x	x	x	x	
2015	Reinforced 3-d printed project	Yingchuang	Cementitious + conventional steel reinforcement	Direct wall extrustion, steel reinforcement and and the pooring of concrete	x	+	+	+	x	x	x		x	x	x	x	x	x	x	
2015	XtreeE 3-d printer	XtreeE	Cementitious	Indirect wall extrustion	x	+	+	+	x	x	x		x	x	x	x	x	x	x	
2014	Contour Crafting	University of Southern California	Cementitious	Direct wall extrustion	x	+	+	+	x	x	x	x	x	x	x	x	x	x	x	x
2011	Concrete Printing	Loughborough Univeristy	Foam or Concrete	Direct wall extrustion		+	+	+	x	x	x		x	x	x	x	x	x	x	

Table 2. Potential cementitious 3-d printing wall applications versus the drivers and barriers to 3-d construction printing; FLAM 3-d printer is suggested as most interesting for the aim of this research.

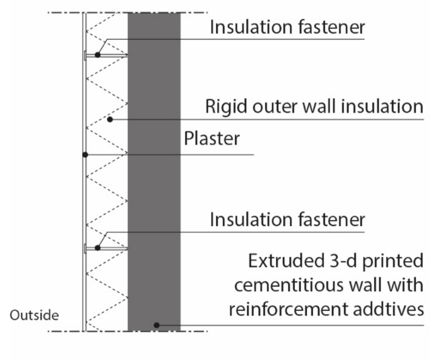
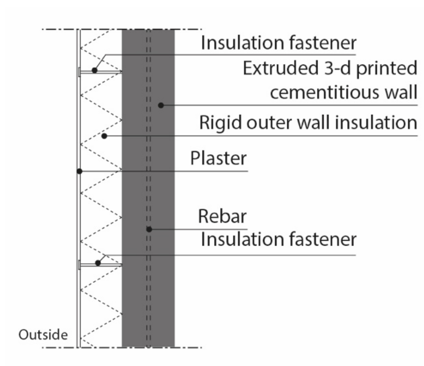
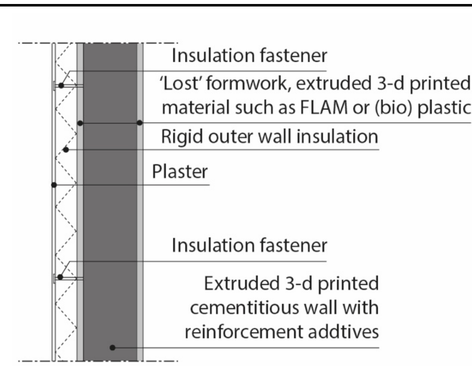
Typology	Description	3-d printer	
(1) Advanced reinforced cementitious wall	Reinforcement additives are mixed in the extruded material. The cementitious wall is 3-d printed. Rigid outer wall insulation is fastened on the outer side of the wall and finished with plastering. Another option could be the use of a 3-d shotcrete printer. Then, the rigid outer wall insulation is manually fastened and plastered for example.	3DCP, Thin Folded Concrete Members, Shotcrete 3-d printing	
(2) Semi advanced reinforced cementitious wall	The cementitious wall (component) is 3-d printed. Reinforcement is placed manually within the designed openings and filled with cemenitious material. Rigid outer wall insulation is fastened on the outer side of the wall and finished with plastering. Optionally, rebar could be 3-d printed.	Apis Cor, MX3D (3-d printed rebar), DCP, WASP 3-d, 3-d Printed Bridge, Reinforced 3-d printed project, Contour Crafting, Concrete printing, Xtree	
(3) Advanced reinforced cementitious wall with lost 3-d printed formwork	The lost formwork is 3-d printed with extruded material such as FLAM or (bio) plastic. In alternation, the cementitious wall is 3-d printed just after hardening of the forkwork. Rigid outer wall insulation is fastened manually on the outer side of the wall and finished with plastering.	Eggshell, FLAM 3-d printer	

Table 3a. Potential cementitious 3-d printing wall typologies, their description and the name of 3-d printer (illustration of author). Benefits of 3-d printing in construction

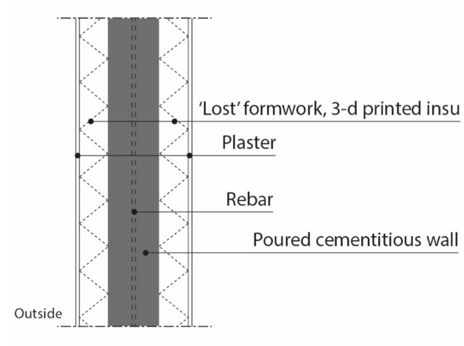
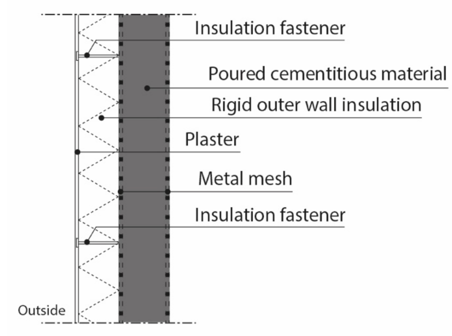
(4) Advanced 3-d printed isulative lost formwork with non-advanced structural cementitious wall	The lost insulative formwork is 3-d printed with extruded insulative material. Thereafter, rebar is placed for reinforcement and the cementitious material is poured into the formwork.	Bati3D 3-d printer, DCP	
Advanced 3-d printed steel lost formwork with non-advanced cementitious wall and outer wall insulation.	Advanced additive manufactured steel lost formwork is made by a robot, the cementitious material is poured manually and thereafter is smoothed by hand. Optionally, the cementitious material can be 3-d printed with a speciallity equipment in form of a extrusion head.	Mesh Mould and In Situ Fabricator, Thin Folded Concrete Members	

Table 3b. Potential cementitious 3-d printing wall typologies, their description and the name of 3-d printer (illustration of author). Benefits of 3-d printing in construction

It is argued that a key benefit of this form of innovative technology is greater efficiency of resources from the point of manufacturing, through construction and use and recycling. Innovative manufacturing improves the flow of materials and contributes to a circular economy, eliminating waste and moving away from "the linear take-make-waste model" (Despeisse et al., 2017, p.1). It also improves the flow of information, which it is suggested could make the construction process more efficient and productive, and as such more sustainable. Gebler et al. (2014) maintain that this technology is a cost-effective way of lowering manufacturing inputs and outputs in markets with low volume, and in customising high-value production chains, lowering energy use, resource demands and related carbon emissions over the entire product life cycle. This in turn can induce changes in labour structures, generating a shift towards more digital and localised supply chains with consequential environmental as well as socio-economic benefits.

Despeisse et al., (2017) maintain that 3-d printing offers a high degree of design freedom, facilitates mass customisation and makes it relatively easy to create custom designs or to make design changes. Thomas & Gilbert (2014) add that 3-d printing permits the use of a diverse range of materials and ensures economies of scale in mass production. The technology enables the reproduction and manufacturing of products without expensive moulds, thus reducing costs and enhancing quality over the life of the product.

Thomas & Gilbert (2014) argue that 3-d printing can reduce fabrication and materials costs during the manufacturing process and the use of these products can also reduce transportation costs and environmental impacts by reducing the volume and frequency of supplies to a site. It also reduces vulnerability to supply chain disruption. A key benefit of additive manufacturing such as 3-d printing is that it can involve localised production, which has associated environmental benefits.

Khoshnevis et al. (2006) suggest that 3-d printing can be used to create a variety of products used in construction, including formwork. Weinstein & Nawara (2015, p.96) maintain that additive manufacturing can be used to develop low-cost housing in a short period, citing examples such as DUS Architects in Amsterdam, who plan to develop "one-of-a-kind 3-d printed houses that architecturally stand out". The project, named the 3-d Canal House, uses sustainable materials, including bioplastics and glue made of 80% vegetable oil. Khoshnevis (2004) also takes the view that additive technologies are the future of construction, with the potential to speed-up construction and the delivery of housing in a materially efficient manner.

McAllister & Wood (2014) point out that 3-d printing is more sustainable than conventional manufacturing, which it is suggested can be translated into carbon savings in the construction process. It is suggested that these benefits tie into the concept of a circular economy, as the technology seeks to optimise the use of materials from sourcing to supply chain and to consumption (Esposito et al., 2015).

The benefits of 3-d printing in the construction industry can also be considered in terms of the supply chain or the value chain. 3-d printing has the potential to disintermediate certain members of the value chain by relocating production away from a production specialist to the 3-d printer itself, creating—at least in theory—a situation in which the architect can interact directly with the 3-d printer and thereby disintermediate some producers. Disintermediation is an example of innovation, as noted by Clayton and Christensen (1997). For example, in the 1990s, the Internet disintermediated traditional travel agents by connecting vacation-seekers directly with airlines and hotels for self-booking purposes. In this example, the Internet had already existed for several years, and travel agencies had existed for decades, so the innovation is not the underlying technology, but the application of an existing technology to an existing need in a novel manner (Clayton & Christensen, 1997). Thus, even though 3-d printing has its intellectual roots in the 1980s and its first production roots in the 1990s, it can still be considered both innovative and beneficial in terms of disintermediation.

Large value chains represent higher costs, higher levels of complexity, and more possible points of project failure. For all of these reasons, the kind of disintermediation made possible by 3-d printing should be considered beneficial to an economy as a whole, even though such disintermediation might be interpreted as problematic by materials producers and certain construction companies. However, even parties who are disintermediated benefit from the disintermediation, as they are forced to provide more valuable services and thereby re-establish themselves on the value chain. Therefore, it should not be assumed that the disintermediating power of 3-d printing is beneficial solely for architects, designers, and clients; the benefits of disintermediation are likely to spread across the entire construction value chain. Questions related to disintermediation were posed to the 3-d printing industry executive who was one of the participants in the qualitative portion of this study.

6.4.1 Drawbacks of 3-d printing in Construction

It is clear that there is a sustainable case for additive manufacturing; however, there are drawbacks to this technology, including a lack of education and skills regarding 3-d printing and the fact that it is still an evolving technology that has yet to be proven in the longer term (Sakin, 2017). De Jong & Wamelink (2008) argue that cost is a crucial element in the development of green buildings. Thomas & Gilbert (2014) also take the view that cost can be an issue - particularly concerning material and equipment costs. In addition, the cost of a 3-d printer is high in comparison with conventional construction according to Savin (2017). Especially, in building elements in low quantities. Therefore, it is suggested to create scale, thus create high output and create a high demand is necessary to lower the unit price.

It is argued that a drawback, not of the technology but of the implementation of this technology in the construction industry, is general reluctance within the industry toward innovation, which can be related to three theoretical strands: innovation typology, the institutional view, and the organisational view (Koskela & Vrijhoef 2001, p.197). The reaction to innovation will depend on the level of change required, where an incremental innovation is defined as a minor change with limited impacts on the surrounding elements, such as the traditional methods of management or construction. A modular innovation has a more notable change, with a limited impact on its surroundings, whereas an architectural innovation may entail a relatively small change, yet it has strong links to other surrounding components and as such can lead to a wide number of changes at organisational and project level, as does system innovation. A radical innovation is essentially a change based on a breakthrough in science or technology, as such a radical change can have industry implications (Koskela & Vrijhoef 2001; Norman & Verganti 2014). It is argued that the use of 3-d printing in the construction process lies somewhere between an architectural change and a potentially radical change, which means that the industry and organisations within the industry must be willing to accommodate the technology by making the appropriate changes to management and supervision of the construction process. Berriman (2017) implies that increased use of robotics and automation in the industry could reduce the need for human labour, which it is suggested could be a barrier to the positive perception of this technology.

Foy & Shahbodaghlou (2015) maintain that drawbacks include finding ways to integrate this new technology with traditional forms of construction and developing a clear framework for the costs associated with the technology. As previously mentioned, the construction industry operates within tight budgets and low levels of profit, which suggests that any technology needs to be developed with a clear understanding of the cost implications for the project and the construction organisation (Walker 2015). The difficulty with 3-d printing is that there is a lack of mature research on 3-d construction printing and the costs of the technology. Moreover, no company offers a commercial available 3-d construction printer for sale. The potential cementitious 3-d printing wall applications, seen in table 2, show 3-d printers which are part of different research projects and are not commercially available. Although Weber Beamix and BAM opened a 3-d printing facility recently, this is still a conceptual facility which is tested in-house (3-d printed house, 2019).

Entering the wrong market or market segment could create a barrier for further adoption. Although it is suggested that 3-d construction printing is a footloose technology, the question remains if there is currently enough demand in the Netherlands for this technology aimed at building new buildings. The potential cementitious 3-d printing wall applications, seen in table 2, seem to be all focused on creating new building structures and not focusing on a product or service for the existing housing stock. In the Netherlands, increasing the building stock is currently high on the political agenda but the current building stock, which needs to be more sustainable, is far greater and is also high on the political agenda. Therefore, the question is if the market for 3-d printing new buildings in the Netherlands is large enough to be commercially viable. The latter or a combination of the two seems to be far more interesting since it is larger in the Netherlands. For example, refitting buildings with insulation is one of the most efficient ways to make a building more sustainable and get a return on investment (Iris, 2019). However, it seems there is no application for it yet, and possibly there is a reason for that.

According to Vos (2015), 3-d printed components are not aligned to the construction process of a building for two reasons. Firstly, there is uncertainty on how to meet the building requirements of the Dutch building code. Secondly, the ultimate construction process of a 3-d printed cementitious outer wall is unclear. This leads to the following: manually assembly of components and inefficient actions during construction; improvised manners to transport and assemble the 3-d printed components; poor connective quality between building components; questionable safety; failing to comply to the Dutch building code; and the combinations of materials that are hard to separate when recycling comes in question at the end of its life cycle (Vos, 2015).

6.4.2 Compare 3-d printing to conventional construction with respect to sustainability, carbon emissions, waste and productivity

Walker et al. (2015) point out that the housing sector is a major contributor to greenhouse gas emissions and climate change, hence the search for a sustainable alternative in the form of zero carbon homes. It is argued that the achievement of zero-carbon homes is extremely difficult using conventional construction, largely because the work is carried out in exposed environmental conditions and is reliant on the skills of each worker to achieve close tolerances and air-tight building fabrication. In contrast, components developed in a factory environment can draw on automated technology to achieve high-quality materials that can be fitted together to form an air-tight building fabric (Lawson et al., 2014). Mao et al. (2013) make the point that pre-fabrication reduces the carbon emissions associated with the construction process. In this study, a quantitative model was developed to compare the carbon footprint of a semi-prefabrication project and a conventional construction project located in China. The research found that the semi-prefabrication method produced fewer carbon emissions per square meter compared with the conventional construction, at 336 kg/m^2 compared to 368 kg/m^2 respectively. It was found that the largest proportion of total carbon emissions, totalling 85%, was from the embodied emissions of building materials. The key factors which contributed to the prefabricated superior performance of the prefabricated units were the embodied carbon emissions of building materials, reductions in transportation emissions of building materials, reduced resource consumption, and reduced waste. It is suggested that this confirms that additive manufacturing and other off-site manufacturing techniques have a smaller carbon footprint than conventional construction.

6.5 Identify the barriers to the use of 3-d printing

A review of the literature suggests the existence of at least fourteen major barriers to the adoption of 3-d construction printing: High printer cost, Immaturity of printing partners, Unclear regulatory implications, Inability to create larger structures, High cost of printed structures, Lack of commercial viability, Lack of customer support, Insufficient successful examples, Architect / designer unreadiness, Difficulty of transporting printer, Technology interruption risk, Need for expensive specialty materials (see table 4).

Overarching barrier	Barriers		
Cost	High printer cost	High cost of printed structures	Need for expensive speciality materials
Market dynamics	Lack of commercial viability	Lack of customer support	
Limitations amongst partners or stakeholders	Architect / designer unreadiness	Immaturity of printing partners	
Construction capacity	Inability to create larger structures		
On-site and off-site logistics	Difficulty of transporting printer		
3-d technology	Technology Interruption risk		
Law	Unclear regulatory implications		
Proof of concept	Insufficient successful examples		
Usability	Design practicality (is the wall itself, holistically practical)	Size of the 3-d printer	

Table 4. Suggested major barriers to the adoption of 3-d construction printing

Of these 14 barriers, 3 (high printed cost, high cost of printed structures, and need for expensive speciality materials) are related to cost, 2 (lack of commercial viability, lack of customer support) to market dynamics, 2 (architect / designer unreadiness and immaturity of printing partners) to limitations among partners or stakeholders, 1 (inability to create larger structures) to construction capacity, 1 (difficulty of transporting printer) to on-site logistics, 1 (technology interruption risk) to 3-d technology, 1 (unclear regulatory implications) to law, 1 (insufficient success examples) to proof of concept and 1 (design practicality, size of the 3-d printer) to usability.

The evidence for the existence of barriers, and a related discussion of possible solutions has been presented below.

In terms of the cost elements of 3-d printing in the construction industry (high printer cost, high cost of printed structures, and need for expensive speciality materials), the category of cost has been described not as much in the domain of owning 3-d printers or leasing 3-d printing services, but in ancillary domains. However, there is evidence that, at least for some companies in some situations, the cost of 3-d printers is also high compared to traditional alternatives (Sakin, 2017; Vinodh et al., 2009). Polymer matrix composites are one of the many materials that have been identified as generating high costs in the context of 3-d printing (Wang et al., 2017). In addition to the cost of some speciality materials that might be more necessary for 3-d printers than for traditional productive alternatives, high costs can also be rooted in the costs of project management (Sakin & Kiroglu, 2017) associated with 3-d printing more so than with traditional constructive alternatives. For these perceived barriers to 3-d printing in the construction industry to be addressed, technology innovators in the 3-d printing domain would have to (a) find a way to reduce the costs of certain raw materials, or, more practically, to configure 3-d printers to be able to work more readily with replacement materials on a case-by-case basis; and (b) find a way to define and disseminate best manages in project management that could reduce cost and complexity for end users who are adopting a 3-d approach to construction. Therefore, the identified barriers of cost high printed cost, high cost of printed structures, and need for expensive speciality materials can also be conceptualised in terms of possible solutions related to innovation in materials handlings, materials management, and the definition and dissemination of best practices in project management related to 3-d printed construction settings and scenarios.

In terms of market dynamics, Kothman and Faber (2016) suggested that end users were not uniformly positively disposed to, or even aware of, 3-d printing for construction. Kothman and Faber (2016) suggested that, in this context, 3-d printing might be similar to blockchain, another disruptive technology that has so far proven to be of more interest to technology-makers and early-stage adopters than to the marketplace in general, even though there is potential for widespread adoption. The issue of market dynamics relating to the adoption of 3-d printing can be considered in terms of the innovator's dilemma, in which, according to Christensen (1997), the innovator is not immediately rewarded with market recognition. Indeed, one key component of the innovator's dilemma is that it can take several years for an innovation to obtain traction within the overall market if such traction is even achieved. Christensen noted that, for example, the videotape format Betamax, which predated the VHS format and thus represented the more profound innovation, was not adopted as broadly by the market as VHS ended up being. As applied to 3-d printing, the issue is therefore that the mass market might not yet have become as enamoured of this technology as vendors and early-stage users are; in the case of video, the case of Betamax indicates that an innovation can, despite its early promise, fail. Therefore, construction companies driven primarily by the wishes and predilections of their end users might experience a barrier in terms of 3-d construction printing adoption (Kothman & Faber, 2016). If such a barrier indeed exists, it could only be removed by the process of organic engagement of the marketplace with the innovation—a process that, according to Christensen, can take years, if it occurs at all. In this respect, one action that both 3-d printing vendors and evangelist users of this technology can take is to better promote 3-d printing in the general public consciousness, whether through marketing or other general activities designed to raise consumer consciousness.

Some of the specific barriers to 3-d printing in the construction industry noted above appear to be based in various considerations of technical or productive sufficiency. In this respect, it should be noted that, despite having made profound technological advances in the real world of construction, there appear to be cases in which 3-d construction printing might possess certain production weaknesses. For example, the usefulness of 3-d printing with the use of

cementitious materials is still being improved, with innovators in this domain acknowledging the potential solutions to problems of complexity are still in their early stages, unproven in numerous actual production environments. A specific example of such a weakness of 3-d printing, a weakness that is still being addressed on ongoing innovation, is the need for temporary supports in the creation of complex, large-scale geometries (Gosselin et al., 2016). In table 2, there is no project realised yet which proves that large scale projects are possible, such as a building with multiple floor levels. However, the 3-dCP project from the University of Eindhoven promises to build a building with multiple floors through 3-d printed components as a proof of concept. For considerations of technical or productive sufficiency to be adequately addressed, it is necessary for innovation to continue to take place and for new solutions to become adequately demonstrated in the real world to provide proof-of-concept for potentially hesitant adopters. One of the components of the innovator's dilemma (Christensen, 1997) is the period during which the disruptive technology has to be defined and perfected so that it can definitely be said to constitute an improvement over the technology that it is replacing without posing risk or higher costs to adopters. Thus, the solution to the barrier of perceived immaturity—whether this immaturity is located at the level of the underlying technology of 3-d printers, the reliability of 3-d printing technology companies, or the reliability of the actual structures and components that emanate from 3-d printing—is simply continued innovation of the kind described by Christensen. One risk underlying this process is the risk of technology interruption. For example, as Gosselin et al., noted with reference to new approaches that eliminate the need for support structures when creating large-scale, complex-geometry cementitious structures, the market currently depends on continuing innovation from scientists. Should the timing of such innovations be delayed, there is a concomitant risk to adopters of 3-d printing technology in certain contexts. Therefore, the market at large is dependent not just on ongoing innovation but on the lapse of a longer period of time after which certain innovations can become embedded and the
risk of technology interruption is thereby lessened.

Table 5 below contains De Schutter et al.'s (2018) identification of specific obstacles to 3-d printing in construction:

Barrier Type	Description
Material choice	Many current showcases are not based on high-quality materials required to reach a reasonable service live in natural or industrial exposure conditions. They are rather narrowly based on the technological issue of being able to add layers on top of each other without premature collapse. When checking material performance in some showcases in more detail, striking insufficient performance can sometimes be noticed…
Active control of rheology and stiffening	The problem while placing concrete is that the rheological properties cannot be actively adjusted during the casting process. Based on mix design and mixing procedure, the concrete will show its particular rheological behaviour, only further influenced by environmental conditions and duration of the casting process.
Mechanical and durability performance	Current structural and durability design codes consider the concrete as a homogeneous material. For 3-d printed concrete elements, this is no longer the case, due to the layered concept with more porous and weaker interfaces, and anisotropic behaviour. Structural design will have to consider the layered structure, requiring new design models, e.g. for shear loading. The structural design models will further have to consider that reinforcement will most probably no longer be provided in the traditional way, introducing new reinforcement concepts.
Integration of reinforcement	Integration of vertical reinforcement in 3-d printed concrete elements is a critical challenge to which no satisfactory solutions are not available yet. This will be a prerequisite to fully utilise the geometrical freedom and topological optimisations as well as to broaden the application spectrum of digital fabrication with cementitious materials.

Table 5: De Schutter et al.'s Identified Obstacles to 3-d Printing in the Construction Industry

7 Research Methodology

This section sets out the methodology used to progress this thesis. The research methodology has been divided into the following sections. First, the design of the study has been discussed with reference to its quantitative and qualitative components. Second, sampling has been discussed. Third, the measures of the quantitative portion of the study have been provided. Fourth, both quantitative and qualitative data collection for the study was discussed. Fifth, both quantitative and qualitative data analysis for the study were discussed. Sixth, the limitations of the study's methodology were acknowledged. Seventh, ethical issues related to the study were discussed.

7.1 Study design

The study design of the study is mixed-methods, meaning that quantitative and qualitative methodologies have been combined in the study. A quantitative methodology is one in which the sole means of data analysis is based on mathematical analysis of a phenomenon or the relationships between phenomena (Creswell, 2015). A quantitative methodology was selected for the second aim of study because the research problem and purpose of the study were both based on a lack of knowledge about the significance and magnitude of obstacles to 3-d printing in the construction industry. The terms *significance* and *magnitude* were defined in explicitly mathematical terms, as briefly noted in the introduction of the study. Therefore, only a quantitative methodology could be applied to the study. The design was descriptive in that the gathered questionnaire results were analysed on their own, without reference to either an independent variable or covariates. In the absence of an independent variable, the study was not subject to experimental, quasi-experimental, or correlational designs. A descriptive design, on the other hand, is suited to research scenarios in which survey data or other data are analysed to build basic knowledge about a phenomenon (Creswell, 2015). Therefore, a descriptive design was suited to the second aim of this study. The third aim of this study required a qualitative approach. A qualitative approach was chosen because, in speaking to experts in the 3-d construction printing industry (architects and senior executives at 3-d construction printing organisations), the purpose is to synthesise and analyse multiple responses from many respondents but at the same time to explore rich narratives based in real-world use scenarios. These narratives offered a means of exploring the barriers to 3-d printing emerging from a specific use case (that of cementitious outer walls) and based on aspects of radical innovation as discussed in the literature review. It was suggested, that due to the fact of the relative newness of the 3-d construction printing industry, and given that the technology according to Moore (2014) is still in the innovator's stage, that the research pool is (too) small for architects with real-world experience in 3-d construction printing. Therefore, to create a larger group with a sufficient number of participants, the participants were chosen on their expertise in 3-d construction printing, instead of solely their profession in architecture. It was therefore assumed that senior executives at 3-d construction printing organisations also (partly) have the knowledge needed to answer questions relating to the third aim of the study. However, the interviews questions were divided by their profession. Two qualitative interviews were made, (1) for architects with real-world experience in 3-d construction printing and (2) for senior executives at 3-d construction printing organisations. In the two interviews, questions overlap, and some were specified to the participant's specific background.

7.1.1 Sampling; cases and respondents

Regarding the questionnaire study, it is acknowledged that the reliability and validity of the findings of this study are linked to the sample of people used in the questionnaire study. Therefore, given the importance of the sample size and the way in which this sample represents the wider 3-d construction printing industry, the sample will be selected. This will entail inviting 3-d construction printing professionals such as architects with real-world experience in 3-d construction printing and executives of 3-d construction printing companies to participate in the study, with representatives from the architecture sector and the 3-d construction printing manufacturing sector, with a balanced number of participants from each sector. This should provide an insight into 3-d printing from different perspectives (Farrell, 2011; Naoum, 2012). The intention was to use purposeful selective sampling, approaching a select number of organisations based on their track record in the architecture sector or the 3-d manufacturing sector.

Although differences in perspectives between countries are expected because of varying national drivers for innovation, the construction industry operates within the European economic zone and under European legislation. Therefore, the geographical location of the respondents is limited to the European Union. 3-d printing is eminently a footloose technology, flexible to ship and apply in another geographic location. Because of increasing globalisation and the assumed international nature of a technology as 3-printing, excluding respondents from EU countries, would likely lead to missing important information on the construction industry's perspective on 3-d construction printing.

The value of the data collected is dependent on the knowledge and experience of the participants, with specific inclusion criteria being the experience of construction, resource management and logistics, as well as having a basic knowledge of 3-d construction printing and off-site manufacturing. To this end, the first section of questions in the questionnaire will be developed to assess the value offered by each participant and to determine if the data collected will be included or excluded from the analysis.

Regarding the qualitative portion of the study, data were collected from two type of participants, an architect with real-world 3-d construction printing experience and a senior executive at a 3-d printing organisation.

7.1.2 Measures

7.1.2.1 Measures; quantitative portion of this study

In this study, a questionnaire was designed with several questions that redirected attention at the process of 3-d construction. Consequently, the first part involved gathering of demographic data as a way of screening the study participants. The exact questionnaire with a nice layout, that was send to the participants through SurveryMonkey, can be found in appendix B. The questionnaire was comprised of 36 questions as about as follows:

Q1. What is your background?

Q2. I appreciate you letting me know who you are. I do not want to spam you in any way; the data I collect will be used only for this research.

Name:
Company:
Address :
City/Town:

ZIP/Postal Code:
Country:
Email Address:
Phone Number:
Q3. What is your position?

Q4. How many years' experience do you have within the built environment?

Q5. Are you familiar with 3-d construction printing?

Q6. Are you an expert on 3-d construction printing?

Q7. Do you have real-world experience in 3-d construction printing?

Q8. Why do you consider yourself as a real expert on 3-d construction printing?

Q9. Why do you not consider yourself as a real expert on 3-d construction printing?

Q10. Can you tell me in short in what kind of 3-d construction printing projects you were involved?

Q11. What was your role within the 3-d construction printing projects?

Q12. What were the budgets of these 3-d construction printing projects?

Q13. The cost of purchasing a 3-d construction printer which can print outer wall components ranges from approximately € 350.000, - to €600.000,-. It is suggested, that these printers can 3-d print wall components high enough to build a wall of at least 4 meters high and extrude a wall of at least 10 cm in width (if needed). It is assumed that the insulation of the wall itself is not sufficient to meet the building code, so additional external wall insulation must be placed on the 3-d printed outer wall. Operational costs or maintenance costs are not included in this question. Please answer the question with this in mind and by filling in a number (1-6). In addition, please feel free to give an explanation if you feel this is needed.

I believe that high printer cost is a challenge in the use of 3-d printing in the construction industry (1 = completely disagree, 2 = disagree, 3 = somewhat disagree, 4 = somewhat agree, 5 = agree, 6 = completely agree).

Q14. I believe that the immaturity of printing partners is a challenge in the use of 3-d printing in the construction industry (1 = completely disagree, 2 = disagree, 3 = somewhat disagree, 4 = somewhat agree, 5 = agree, 6 = completely agree) . Please answer the question by filling in a number (1-6). In addition, please feel free to give an explanation if you feel this is needed.

Q15. I believe that finding the right niche market is a challenge in the use of 3-d printing in the construction industry (1=completely disagree, 2 = disagree, 3 = somewhat disagree, 4 = somewhat agree, 5 = agree, 6 = completely agree). Please answer the question by filling in a number (1-6). In addition, please feel free to give an explanation if you feel this is needed.

Q16. I believe that for a company within the built environment, innovating on itself is a challenge in the use of 3-d printing construction printing (1 = completely disagree, 2 = disagree, 3 = somewhat disagree, 4 = somewhat agree, 5= agree, 6 = completely agree). Please answer the question by filling in a number (1-6). In addition, please feel free to give an explanation if you feel this is needed.

Q17. I believe that unclear regulatory implications are a challenge in the use of 3-d printing in the construction industry (1 = completely disagree, 2 = disagree, 3 = somewhat disagree, 4 = somewhat agree, 5 = agree, 6 = completely agree) . Please answer the question by filling in a number (1-6). In addition, please feel free to give an explanation if you feel this is needed.

Q18. In the following question, the term “larger structures” is mentioned. Larger structures are in this case, structures which need (temporary) support structures. Beams, columns, temporary structures, rebar for stiffening and so forth. For this question, a residential building with a width of more than 24 meters and more than 4 floors is considered as a minimum case for the consideration of a ‘larger structure’. Please answer the question with the above mentioned in mind and by filling in a number (1 -6). In addition, please feel free to give an explanation if you feel this is needed.

I believe that the inability to create larger structures is a challenge in the use of 3-d printing in the construction industry (1 = completely disagree, 2 = disagree, 3 = somewhat disagree, 4 = somewhat agree, 5 = agree, 6 = completely agree).

Q19. In the following question, the term ‘cost of printed structures’ is mentioned. With the cost of printed structures, we mean the cost of materials used to print a component or construction. For example, materials such as polymer matrix composites are often used to give the construction more strength. Please answer the question with this in mind and by filling in a number (1-6). In addition, please feel free to give an explanation if you feel this is needed.

I believe that the high cost of printed structures is a challenge in the use of 3-d printing in the construction industry (1=completely disagree, 2 = disagree, 3 = somewhat disagree, 4 = somewhat agree, 5 = agree, 6 = completely agree). Please answer the question by filling in a number (1-6) and an optional explanation.

Q20. In the following question, the term ‘commercial viability’ is mentioned. Commercial viability is the ability of a business, product, or service to compete effectively and to make a profit. Please answer the question with this in mind and by filling in a number (1-6). In addition, please feel free to give an explanation if you feel this is needed.

I believe that the lack of commercial viability is a challenge in the use of 3-d printing in the construction industry (1 = completely disagree, 2 = disagree, 3 = somewhat disagree, 4 = somewhat agree, 5 = agree, 6 = completely agree).

Q21. In the following question, the term ‘Customer support’ is mentioned. Customer support is a range of customer services to assist customers in making cost effective and correct use of a product. It may include the assistance in planning, installation, training, troubleshooting, maintenance, upgrading, and disposal of a product. Please answer the question with this in mind and by filling in a number (1-6). In addition, please feel free to give an explanation if you feel this is needed.

I believe that lack of customer support is a challenge in the use of 3-d printing in the construction industry (1 = completely disagree, 2 = disagree, 3 = somewhat disagree, 4 = somewhat agree, 5 = agree, 6 = completely agree).

Q22. I believe that insufficient successful examples are a challenge in the use of 3-d printing in the construction industry (1 = completely disagree, 2 = disagree, 3 = somewhat disagree, 4 = somewhat agree, 5 = agree, 6 = completely agree). Please answer the question by filling in a number (1-6). In addition, please feel free to give an explanation if you feel this is needed.

Q23. I believe that architect / designer unpreparedness a challenge in the use of 3-d printing in the construction industry (1 = completely disagree, 2 = disagree, 3 = somewhat disagree, 4 = somewhat agree, 5 = agree, 6 = completely agree). Please answer the question by filling in a number (1-6). In addition, please feel free to give an explanation if you feel this is needed.

Q24. In the following question, the difficulty of transporting a 3-d construction printer for on –site use is discussed. The printer needs to be able to easily arrive on- site for construction purposes. The weight and measurements of the 3-d construction printer, the accessibility of the construction site/roads are of importance. Please bear in mind that prefab components/compartments need to be transported in any case. Please answer the question with the above mentioned in mind and by filling in a number (1-6). In addition, please feel free to give an explanation if you feel this is needed.

I believe that the difficulty of transporting 3 –d construction printers is a challenge in the use of 3-d printing in the construction industry (1 = completely disagree, 2 = disagree, 3 = somewhat disagree, 4 = somewhat agree, 5 = agree, 6 = completely agree).

Q25. In the following question, the term ‘Technology interruption risk’ is mentioned. For example, with reference to new approaches that eliminate the need for support structures when creating large-scale, complex-geometry cementitious structures, the market currently depends on continuing innovation from scientists. Should the timing of such innovations be delayed, there is a concomitant risk to adopters of 3-d printing technology in certain contexts. Therefore, the market at large is dependent not just on ongoing innovation but on the lapse of a longer period of time after which certain innovations can become embedded and the risk of technology interruption is thereby lessened. Please answer the question with this in mind and by filling in a number (1- 6). In addition, please feel free to give an explanation if you feel this is needed.

I believe that technology interruption risk is a challenge in the use of 3-d printing in the construction industry (1 = completely disagree, 2 = disagree, 3 = somewhat disagree, 4 = somewhat agree, 5 = agree, 6 = completely agree).

Q26. In the following question, the term “specialty materials” is mentioned severally. Specialty materials are commercial materials made in very low quantities compared to general-purpose materials, generally of the high price but with specific effect or properties not shared with others. Also, project management to manage these specialty materials fall under this category. Please answer the question with this in mind and by filling in a number (1-6). In addition, please feel free to give an explanation if you feel this is needed.

I believe that the need for expensive specialty materials is a challenge in the use of 3- d printing in the construction industry (1 = completely disagree, 2 = disagree, 3 = somewhat disagree, 4 = somewhat agree, 5 = agree, 6 = completely agree).

Q27. I believe that within the built environment, 3-d Construction Printing is present in the mind of the people (1 = completely disagree, 2 = disagree, 3 = somewhat disagree, 4 = somewhat agree, 5 = agree, 6 = completely agree). Please answer the question by filling in a number (1-6). In addition, please feel free to give an explanation if you feel this is needed.

Q28. I believe that within our company, 3-d Construction Printing is going to be a mainstream technology and therefore it is high on the company’s agenda (1 = completely disagree, 2 = disagree, 3 = somewhat disagree, 4 = somewhat agree, 5 = agree, 6 = completely agree). Please answer the question by filling in a number (1-6). In addition, please feel free to give an explanation if you feel this is needed.

Q29. What is your best or worst experience with 3-d Construction Printing a cementitious outer wall? Please mention the use case.

Q30. Considering the three pictures and their description above; do you think that the fabrication of customized objects with a FLAM 3- d printer for molds, but at the same time also for direct extruded objects, could be a niche market for 3-d building components in Europe? Please, explain.

Q31. Can you think of niches to the 3-d construction printing of an outer wall? Please, explain. Suggestions for the niches are (lost) formwork by using particular biomaterials, 3-d printing of ornaments, special structures, special conditions, 3-d printing of insulation etc.

Q32. Can you think of other general challenges, relating Respondent skipped this question the challenges to 3-d printing a cementitious outer wall that was missing in the questionnaire?

Q33. Do you have a tip or a top for 3-d construction printing an outer wall?

Q34. Do you have a tip or a top for this survey?

Q35. Participants are needed for the third aim of the research, which is to conduct a qualitative analysis of a specific challenge in 3 –d printing in construction, namely the design practicality for the 3-d printing of an outer wall. In short, I need interviewers for the third part of my research, would it be possible to interview you? It would give my research the boost that it deserves, and I would very much appreciate it. Also, the results will be shared with you if you like. The interview will be by phone.

Q36. If you want to be informed about the results of this survey, please tick the box [ ].

7.1.2.2 Measures; qualitative portion of this study

Measures were also undertaken to help gather data from the qualitative portion of this study. Hence, the architects who participated in this research were asked the following questions:

Background information for Q1:

The picture below shows a 3-d printed mould made with fungal-like adhesive materials (FLAM).

According to Fernandez (2019), FLAM is described as follows:

'a fully biodegradable and ecologically sustainable material that is made from cellulose and chitin, the two most common natural polymers and industrial byproducts on Earth. The cost of FLAM is less than 2$/kg, similar to commodity plastics and is 10 times lower than the cost of common filaments for 3-d printing. This material can also be used to 3-d print large structures for objects such as an outer wall' (Fernandez, 2019, p. 1). FLAM has similar structural properties as wood-like materials (Sanandiya, 2018).

FLAM's incorporation into a 3-d printed cementitious outer wall requires an open structure to dry the material with heated air. Afterwards, the cementitious outer wall needs to be plastered with FLAM material and sanded, suggesting the importance of value-added on- or off-site processes that come after the 3-d printing itself (Sanandiya et al., 2018).

Figure 1. 3-d printed mould made with fungal-like adhesive materials (FLAM), credits: Fernandez (2019)

Q1: Can you please describe how FLAM (*Fungal*-Like Additive Material) might be integrated into a 3-d-printed cementitious outer wall, and what the cost and insulative implications of such an approach might be?

Q2: How would you characterise the innovative capacities of 3-d printing with reference to the design and function of a cementitious outer wall?

<u>Background information Q3:</u>

Q3 is about the business model canvas and its 9 categories. For information relating the meaning of the 9 categories of the business model canvas, please see the following link or Appendix A (see p. 8): https://upload.wikimedia.org/wikipedia/commons/1/10/Business_Model_Canvas.png

Q3: Peigneur & Osterwalder (2010) translated the business model into a scheme called the business model canvas which describes the following 9 categories: (1) Value Proposition, (2) Customer Segments, (3) Channels, (4) Customer Relationships, (5) Key Activities, (6) Key Resources, (7) Key Partners, (8) Revenue Streams, (9) Cost Structures. Can you please discuss per category ways in which 3-d printing technology effect the business model, particularly in the domain of cementitious materials (and, if possible, with reference to outer walls)?

Q4: Can you please discuss examples of how 3-d printing has been utilised to innovate new approaches to cementitious construction, particularly of outer walls?

Q5: Can you please discuss the disintermediating capability of 3-d printing?

Q6: In what ways might the disintermediating capability of 3-d printing be beneficial?

Q7: In what ways might the disintermediating capability of 3-d printing be harmful?

Q8: Can you please discuss ways in which 3-d printing technology has been combined with other aspects of robotics to result in innovations, particularly in the domain of cementitious materials (and, if possible, with reference to outer walls)?

Q9: Can you please discuss ways in which 3-d printing technology has been combined with other materials (such as FLAM) to result in innovations, particularly in the domain of cementitious materials (and, if possible, with reference to outer walls)?

Q10: Can you please discuss ways in which 3-d printing technology has altered the construction value chain, particularly in the domain of cementitious materials (and, if possible, with reference to outer walls)?

Q11: Can you please discuss ways in which 3-d printing technology has supported architects' design freedom, particularly in the domain of cementitious materials (and, if possible, with reference to outer walls)?

Q12: Can you please describe how the use of alternatives to 3-d printing might provide the architect with design freedom in tasks related to cementitious outer walls?

Q13: What are some possible barriers to the use of 3-d printing for the design of a cementitious outer wall?

Q14: How might the barriers to the use of 3-d printing for the design of a cementitious outer wall be overcome?

Background information Q15 and the next other upcoming questions:
Appendix B shows different cross-sections of suggested potential cementitious 3-d printing wall typologies and their description.

Q15: I will you show you now different cross-sections of suggested potential cementitious 3-d printing wall typologies and their description. On the basis of this information, what are some possible barriers to the use of 3-d printing for the design of a cementitious outer wall?

Q16: How might the barriers that where suggested by you in the last question be overcome?

Q17: Do you have (an) other potential typology/typologies in mind? And if yes, could you explains how it looks like?

Q18: Could you discuss the barriers of the typology/typologies?

Q19: How might the barriers of the last question of the typology/typologies be overcome?

7.1.3 Data collection procedures

Questionnaires were sent out to multiple organizations with knowledge on 3-d printing and its application in the construction industry. It took two weeks to send the first questionnaires. After a week, reminders were sent. All quantitative data gathering were conducted from the Survey Monkey Platform. On the other hand, qualitative data were collected through telephone calls. Data that were gathered from the architect who agreed that they are going to take part in the qualitative aspect of the study were subsequently gathered basing on a taped telephone call that took 50 minutes. In each case, agreement with the participants was crucial. Data gathered was then transcribed into Microsoft Word to aid understanding. Information that was collected from executives or top management officials of companies that uses 3-d printing technology were as well collected through a taped telephone call that lasted for 50 minutes for each study participant. In this case again, data was transcribed into Microsoft Word. All pieces of data were solely gathered by the researcher to ensure that different pieces were brought together to aid the documentation of this research.

7.1.4 Data analysis

The study realized a considerably low response rate, and so, measures had to be implemented to improvise its transferability. In so doing, the study adopted a bootstrapping analysis provision in the SPSS software. However, a point of concern for bootstrapping is the level of confidence that was to be achieved. For instance, considering a 95% interval, a higher mean, which is above 4 for most of the study questions, could not be reached. For instance, consider the table below, which compares the years a person has within the built environment and if at all they are familiar with 3-d construction printing. For the convenience of analysis, the indicators were structured through a Likert scale as shown below:

1: Less than 5 years

2:5-10 Years of experience

3: 10-15 years

4: over 15 years

Over more than 10 years of working in the built environment was considered a threshold (a sizeable experience for someone to understand the intricacies of the built environment) and even the possibility of having knowledge of 3-d- printing in the construction industry. The study compared question 4 (How many years of experience do you have in the construction industry) and question 5 (are you familiar with 3-d printing in the construction industry). The objective was that an individual who has been in the built environment for several years ostensibly has higher chances of understanding the problems associated with 3-d printing. Analysis of the results is as shown below in table 6.

			Statistic	Bootstrap[a]			
				Bias	Std. Error	95% Confidence Interval	
						Lower	Upper
N	Valid	Q4	9	0	0	9	9
		Q5	9	0	0	9	9
	Missing	Q4	0	0	0	0	0
		Q5	0	0	0	0	0
Mean		Q4	2.67	.01	.52	1.67	3.66
		Q5	1.33	-.03	.27	1.00	2.10
Std. Deviation		Q4	1.323	-.112	.151	.885	1.497
		Q5	.707	-.165	.312	.000	1.051
Skewness		Q4	-.046	-.023	1.057	-2.961	1.821
		Q5	2.121	-.128[b]	.996[b]	.[b,c]	.[b,c]
Std. Error of Skewness		Q4	.717				
		Q5	.717				
Minimum		Q4	1				
		Q5	1				
Maximum		Q4	4				
		Q5	3				

a. Unless otherwise noted, bootstrap results are based on 80 bootstrap samples

b. Based on 80 samples

c. A 95% confidence interval requires at least 39 bootstrap samples.

Table 6. Statistics question 4 and 5 (table of author).

From the table 6 above, the sample mean is considerably lower than the threshold, which is 4 for the Likert scales. For the table 6 above, a sample size of 40 was used to bootstrap and to understand the response if more people would have been involved in the study. For a 95% CI, the highest mean for question 4, which dictated the experience and its association to the possibility of having knowledge of 3-d printing, the highest mean obtained was 3.66 which is still considerably lower than the expected mean of 4. When comparing the experience and the likelihood that an individual should have knowledge of 3-d printing technology in the construction industry, the study failed to realize significant correlations.

7.1.4.1 Challenges to the adoption of 3-d construction printing technologies in the build environment

This is a sectional analysis of the responses of the various respondents in the study. For this analysis, a mean response of 4 will indicate that the respondents ascertained the barrier, as highlighted by the question.

Question 13: *The cost of purchasing a 3-d construction printer which can print outer wall components, ranges from approximately € 350.000, - to €600.000, -. It is suggested that these printers can print 3-d wall components high enough to build a wall of at least 4 meters high and extrude a wall of at least 10 cm in width (if needed). It is assumed that the insulation of the wall itself is not sufficient to meet the building code, so additional external wall insulation must be placed on the 3-d printed outer wall. Operational costs or maintenance costs are not included in this question. Please answer the question with this in mind and by filling in a number (1-6). In addition, please feel free to give an explanation if you feel this is needed.*

I believe that high printer cost is a challenge in the use of 3-d printing in the construction industry (1 = completely disagree, 2 = disagree, 3 = somewhat disagree, 4 = somewhat agree, 5 = agree, 6 = completely agree).

From this question, the study hypothesized that a higher printer costs is an obstacle to the use of 3-d construction printing. This should have been ascertained by analysis of the respondent results. However, analysis of the data (sample of 9 respondents) failed to show that this was the case. The mean is 3.22 which is lower than 4, meaning that the participants did not find higher printer cost to be an obstacle to the adoption of 3-d technology in the printing industry. Tabular exhibits are shown below in table 7a, 7b and figure 2:

N	Valid	9
	Missing	0
Mean		3.2222
Std. Deviation		1.78730

Skewness	.418
Std. Error of Skewness	.717

Table 7a. Statistics question 13 (table of author).

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Completely disagree	1	11.1	11.1	11.1
	Disagree	4	44.4	44.4	55.6
	somewhat agree	1	11.1	11.1	66.7
	Agree	2	22.2	22.2	88.9
	completely agree	1	11.1	11.1	100.0
	Total	9	100.0	100.0	

Table 7b. Statistics question 13 (table of author).

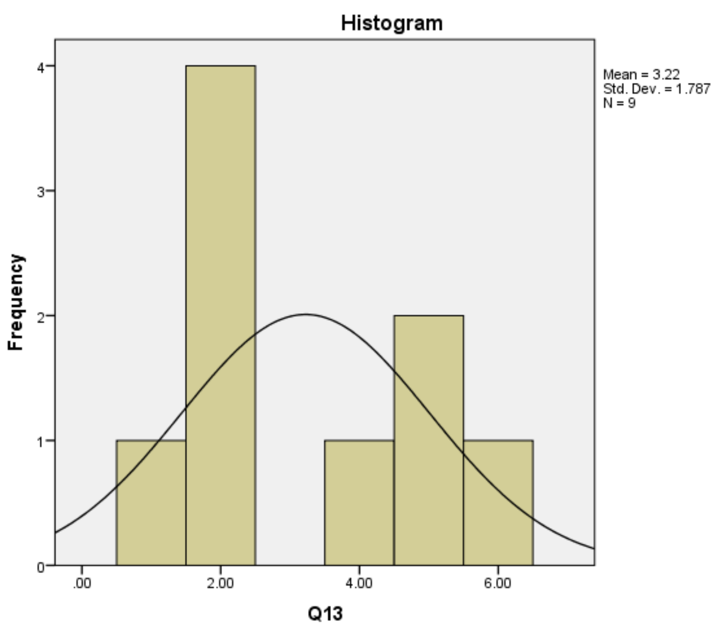


Figure 2. Histogram question 13; Mean= 3.22, Std Dev. = 1.787, N=9 (table of author).

Thus, for question 13, the results fail to justify the assumption that higher printer cost is a factor negative to the adoption of the 3-d printing technologies in the construction industry. However, due to small sample size, it is imperative to extrapolate the results and to identify the perspectives of a considerably larger sample. Using a higher sample size of 85 samples and 95% confidence interval, the study realized a mean of 4.66, which is higher than threshold of 4. The bootstrapped sample shows that higher printer cost is a barrier to the adoption of 3-d printing technology in the construction industry.

		Statistic	Bootstrap[a]			
			Bias	Std. Error	95% Confidence Interval	
					Lower	Upper
N	Valid	9	0	0	9	9
	Missing	0	0	0	0	0
Mean		3.2222	.0042	.5442	2.2255	4.6634
Std. Deviation		1.78730	-.12810	.25055	1.00275	2.12766
Skewness		.418	.001	.822	-1.582	2.396
Std. Error of Skewness		.717				

a. Unless otherwise noted, bootstrap results are based on 80 bootstrap samples

Table 8. Statistics question 13, with bootstrap included (table of author).

Additionally, for study question 14, it was discovered that the immaturity of printing partners is an challenge in the use of 3-d printing in the construction industry), a mean, standard deviation, and 95% confidence interval of the mean were calculated; if the mean were to be significantly higher than 4, it would be concluded that participants found the immaturity of printing partners to be a significant obstacle to the adoption of 3-d printing in the construction industry.

		Statistic	Bootstrap[a]			
			Bias	Std. Error	95% Confidence Interval	
					Lower	Upper
N	Valid	8	0	0	8	8
	Missing	0	0	0	0	0
Mean		3.5000	-.0297	.5938	2.2537	4.6250
Std. Deviation		1.69031	-.16242	.23803	.99309	1.90694
Skewness		-.355	.073	1.029	-2.828	1.538
Std. Error of Skewness		.752				

a. Unless otherwise noted, bootstrap results are based on 80 bootstrap samples

Table 8. Analysis question 14 (table of author).

From the table above (analysis of question 14), the bootstrapped analysis indicates that the immaturity of printing partners is a barrier to the adoption of the 3-d printing in the construction industry, as indicated by the upper mean. However, the analysis shows a wider variation between the lower and upper mean, indicating that the results are not as accurate as expected. This can result from the considerably larger proportion of extrapolation or the higher confidence interval of 95.

Were the analysis to use a lower confidence interval, there could be lower variation in the lower and upper mean; however, the upper mean shows that there is some form of correlation between the immaturity of printing partners as an obstacle to the adoption of 3-d printing technology in the construction industry.

A similar analysis was conducted for the other questions to understand some other barriers to the adoption of 3-d printing technologies in the construction industry. In survey question 15, the study attempted to understand whether or not finding the right niche market is a challenge in the use of 3-d printing in the construction industry. Equally, for question 16, the study, attempted to understand whether for a company within the built environment, innovating on itself is a challenge in the use of 3-d printing construction printing. The threshold value was 4, and as indicated in the analysis, for question 15, the analysis fails to ascertain the role of niche market; finding the right niche market is not a challenge in the use of 3-d printing in the construction industry as per the analysis. For question 16, innovation plays an essential role for a company to remain competitive and to implement the use of 3-d printing within the built environment.

For survey (Q.17, unclear regulatory implications are an obstacle in the use of 3-d printing in the construction industry, a mean, standard deviation, and 95% confidence interval of the mean were calculated to determine whether the point estimate of the mean was significantly different from 4; if the mean were to be significantly higher than 4, it would be concluded that participants found unclear regulatory implications to be a significant obstacle to the adoption of 3-d printing in the construction industry. For survey question (Q.18, the inability to create larger structures is an obstacle in the use of 3-d printing in the construction industry), a mean, standard deviation, and 95% confidence interval of the mean were calculated to determine whether the point estimate of the mean was significantly different from 4; if the mean were to be significantly higher than 4, it would be concluded that participants found the inability to create larger structures to be a significant obstacle to the adoption of 3-d printing in the construction industry.

The tabular analysis of questions 15-18 are shown in table 9 below.

	Statistic	Bootstrap[a]			
		Bias	Std. Error	95% Confidence Interval	
				Lower	Upper

N	Valid	Q15	8	0	0	8	8
		Q16	8	0	0	8	8
		Q17	8	0	0	8	8
		Q18	8	0	0	8	8
	Missing	Q15	0	0	0	0	0
		Q16	0	0	0	0	0
		Q17	0	0	0	0	0
		Q18	0	0	0	0	0
Mean		Q15	2.5000	-.1062	.6134	1.3750	3.4963
		Q16	4.3750	.0266	.4919	3.2537	5.2463
		Q17	3.6250	-.1906	.5326	2.3787	4.6250
		Q18	3.2500	-.1563	.7044	1.7537	4.5000
Std. Deviation		Q15	1.77281	-.21920	.52655	.51755	2.37216
		Q16	1.59799	-.19899	.45571	.70820	2.19751
		Q17	1.76777	-.08279	.29488	.83916	2.18604
		Q18	1.98206	-.14477	.34120	1.03586	2.44674
Skewness		Q15	1.231	-.208	.735	-.626	2.818
		Q16	-1.378	.605	1.029	-2.290	1.437
		Q17	-.275	.254	.676	-1.319	1.530
		Q18	.128	.181	.909	-1.531	2.319
Std. Error of Skewness		Q15	.752				
		Q16	.752				
		Q17	.752				
		Q18	.752				

a. Unless otherwise noted, bootstrap results are based on 80 bootstrap samples

Table 9. Analysis question 15-18 (table of author).

Further analysis was conducted for questions 20-26 to ascertain the implications of other indicators to the adoption of 3-d printing in the construction industry. Analysis is shown below in table 10.

			Statistic	Bootstrap[a]			
				Bias	Std. Error	95% Confidence Interval	
						Lower	Upper
N	Valid	Q19	8	0	0	8	8
		Q20	8	0	0	8	8
		Q21	8	0	0	8	8
		Q22	8	0	0	8	8
		Q23	8	0	0	8	8
		Q24	8	0	0	8	8
		Q25	8	0	0	8	8
		Q26	8	0	0	8	8
	Missing	Q19	0	0	0	0	0
		Q20	0	0	0	0	0
		Q21	0	0	0	0	0
		Q22	0	0	0	0	0
		Q23	0	0	0	0	0
		Q24	0	0	0	0	0
		Q25	0	0	0	0	0
		Q26	0	0	0	0	0
Mean		Q19	3.3750	.1250	.5785	2.5037	4.7426

	Q20	3.3750	.1141	.5616	2.1361	4.5000
	Q21	3.3750	.0719	.5208	2.0074	4.5000
	Q22	3.7500	.0672	.6029	2.6287	5.1176
	Q23	4.1250	.1203	.5146	2.7537	5.1213
	Q24	3.2500	.1234	.6099	2.0037	4.4963
	Q25	3.2500	.1078	.6257	2.0074	4.3750
	Q26	2.6250	.0500	.4241	1.8750	3.3750
Std. Deviation	Q19	1.68502	-.19023	.38799	.53964	2.02996
	Q20	1.76777	-.15975	.34185	.88729	2.26394
	Q21	1.68502	-.18454	.36570	.53964	1.99513
	Q22	1.83225	-.21967	.33926	.88757	2.25056
	Q23	1.55265	-.28605	.46335	.35679	2.04915
	Q24	1.83225	-.15282	.31580	1.07278	2.32762
	Q25	1.90863	-.18042	.32125	.51755	2.13608
	Q26	1.50594	-.09664	.23491	.83916	1.92371

a. Unless otherwise noted, bootstrap results are based on 80 bootstrap samples

Table 10. Analysis question 20-26 (table of author).

For the analysis of question 21-26, as hypothesized, the mean analysis indicates that most of the problems initially highlighted impede the use of 3-d printing in the construction industry. However, question 26, goes against the hypothesis as its mean (both for the initial sample and bootstrapped sample fail to reach the threshold of 4; implying that that the need for expensive specialty materials is not an obstacle in the use of 3-d printing in the construction industry.

Qualitative data analysis was also carried out in the study.

The first qualitative research question of the study was as follows: From the perspective of an architect, what the envisioned barriers to the adoption of 3-d printing for the design of cementitious outer walls? This question was answered primarily through data collected in response to the fifth interview question that was posed to the architect: What are some possible barriers to the use of 3-d printing for the design of a cementitious outer wall? However, the existence of barriers was also sought in the possibility that 3-d printing did not provide the architect with design freedom, a possibility that was encompassed in the open-ended question posed to the architect: Can you please describe how the use of 3-d printing might provide you with design freedom in tasks related to cementitious outer walls? Potential barriers to 3-d printing were also sought through the question that asked the architect about the role of FLAM: Can you please describe how FLAM might be integrated into a 3-d-printed cementitious outer wall, and what the cost and insulative implications of such an approach might be? Also, the architect was asked on characterising the innovative capacities of 3-d printing to discover potential barriers: How would you characterise the innovative capacities of 3-d printing with reference to the design and function of a cementitious outer wall?

The second qualitative research question of the study was as follows: From the perspective of an architect, how can envisioned barriers to the adoption of 3-d printing for the design of cementitious outer walls be overcome? Data for this question were sought primarily from the following interview question: Q6: How might the barriers to the use of 3-d printing for the design of a cementitious outer wall be overcome?

The third qualitative research question of the study was as follows: From the perspective of a 3-d printing manufacturer, what are the envisioned barriers to the adoption of 3-d printing for the design of cementitious outer walls? The 3-d printing company executive was asked about barriers directly (What are some possible barriers to the use of 3-d printing for the design of a cementitious outer wall?) but also with respect to real-world examples and experiences as elicited by the following interview questions: Can you please discuss examples of how 3-d printing has been utilized to innovate new approaches to cementitious construction, particularly of outer walls? Can you please discuss ways in which 3-d printing technology has been combined with other aspects of robotics to result in innovations, particularly in the domain of cementitious materials (and, if possible, with reference to outer walls)? Can you please discuss ways in which 3-d printing technology has been combined with other materials (such as FLAM) to result in innovations, particularly in the domain of cementitious materials (and, if possible, with reference to outer walls)? Can you please discuss ways in which 3-d printing technology has altered the construction value chain, particularly in the domain of cementitious materials (and, if possible, with reference to outer walls)? Can you please discuss ways in which 3-d printing technology has supported architects' design freedom, particularly in the domain of cementitious materials (and, if possible, with reference to outer walls)? As stated, these questions offered the opportunity for the 3-d printing company executive to identify both successful and unsuccessful use cases, the latter of which can be extrapolated into barriers. The semi-structured nature of the qualitative interview also provided the researcher with ad hoc opportunities to ask the 3-d printing company executive about 3-d printing barriers in each of these real-world practice domains.

The fourth qualitative research question of the study was as follows: From the perspective of a 3-d printing manufacturer, how can envisioned barriers to the adoption of 3-d printing for the design of cementitious outer walls be overcome? Data for this question were sought primarily from the following interview question: Q6: How might the barriers to the use of 3-d printing for the design of a cementitious outer wall be overcome? Furthermore, questions related to cementitious 3-d printing wall typologies and their barriers were posed. Data for this question were sought primarily from the following interview questions: Q15: I will you show you now different cross-sections of suggested potential cementitious 3-d printing wall typologies and their description. On the basis of this information, what are some possible barriers to the use of 3-d printing for the design of a cementitious outer wall? Q16: How might the barriers that where suggested by you in the last question be overcome?
Q17: Do you have (a) other potential typology/typologies in mind? And if yes, could you explains how it looks like? Q18: Could you discuss the barriers of the typology/typologies? Q19: How might the barriers of the last question of the typology/typologies be overcome? The next section further gives analysis of the results and findings.

7.2 Research Ethics and Limitations

This study involves gathering of data from professionals with real-world 3-d construction printing experience. Therefore, it is important to make sure that there is a high degree of transparency and ethical values. Up to this point, the individual participants who took part in the questionnaire survey were advised about the goal of the study as well as the manner in which data and information that they will share are going to be used. The goal was the fascination for new technologies in the built environment and of discovering commercially viable products through research. While trying to keep up with the required or acceptable level of academic research ethics, the questionnaire will not capture any confidential of personal information. Moreover, participants of the study were advised accordingly that it is not necessary to answer all questionnaire questions and that the questionnaire can be abandoned completely and all data or information that the participants have shared deleted in case they change their mind about the process or choosing to take part. If preferred by the participant, each study participant will be provided with a copy of questionnaire that has been completed (Biggam, 2015; Gregory, 2003). In addition to that, this study has a wide range of limitations. For instance, quantitative research was basically descriptive. As noted earlier in this research, there are high chances that views and perceptions about 3-d printing technology will be varied between different stakeholders or participants. For instance, the architects could possibly have views about 3-d printing technology that are different from the manufactures and other important stakeholders who are in the construction value chain. Answers from the participants could be influenced by the way the interviewer has asked the questions. The core challenge of the qualitative aspect of this research is that data was strictly retrieved or gathered from two stakeholders.

7.3 Dissemination

As pointed out in the introduction to this research, there is a housing crisis in the Netherlands and a dire need to ensure that the housing gap is filled effectively with qualitative, sustainable and energy-efficient properties while being commercially interesting to design and build buildings. This thesis addresses these problems, and it is therefore argued that the results of this study will provide understanding on the implementation barriers of 3-d printing in the construction industry and on how to potentially overcome these barriers to implement 3-d printing in the construction industry. It will be useful to stakeholders in the construction industry. It may also be useful to urban planners and policy makers, particularly with respect to the construction of residential housing. The deliverable from this research will be the publication of a thesis, set out in chapters and presenting a detailed literature review, data collection, analysis results, conclusion and discussion.

7.4 Results and Findings

From the statistical analysis, the study discovered various indicators impeding the adoption of 3-d technology printing in the built environment. Many of the indicators that were hypothesized to have an effect on the adoption and even use of 3-d printing in the construction industry turned out to be actually having an effect in the adoption of the disruptive technology.

7.4.1 Non-barriers

Question 15: I believe that finding the right niche market is a challenge in the use of 3-d printing in the construction industry.

Initially, the study hypothesized that finding the right niche market is a considerable challenge in the use of 3-d printing technologies. However, the analysis of the findings (both form the initial sample of 9 [1 failed to answer question 15] and the elongated sample, the mean was considerably lower than the value 4, which was the threshold value. It follows that many of the respondents failed to consider finding the right niche market as a challenge to the use of 3-d technology in the built environment. As shown in the table below, the mean value is 2.5 against the threshold value of 4 which quantifies niche market as an obstacle to 3-d printing. With a widespread adoption of the technology, finding the right market for the 3-d printed construction artifacts cannot be a challenge. The results in table 11 indicate that there are more pressing challenges to the adoption of the new technology as opposed to finding a niche market.

		Statistic	Bootstrap[a]			
			Bias	Std. Error	95% Confidence Interval	
					Lower	Upper
N	Valid	8	0	0	8	8
	Missing	0	0	0	0	0
Mean		2.5000	-.0406	.5852	1.3750	3.7500
Std. Deviation		1.77281	-.22349	.47024	.52120	2.32609

a. Unless otherwise noted, bootstrap results are based on 80 bootstrap samples

Table 11. Analysis question 15 (table of author).

Question 26: *In the following question, the term 'specialty materials' is mentioned. Specialty materials are commercial materials made in very low quantities compared to general-purpose* *materials, generally of the high price but with specific effect or properties not shared with others. Also, project management to manage these specialty materials fall under this category.*

It was expected that the need for expensive specialty materials is a barrier to the adoption of 3-d printing in the construction industry. However, from the analysis in table 12, the mean is lower than the expected threshold means of 4 (based on the Likert scale) for it to quantify the indicator as an obstacle to the implementation of 3-d printing technology in the construction industry. The lower standard deviation is a testament that most of the numbers are very close to the mean. A verity of materials, including resins, rubbers, ceramics, glass, concretes, and metals can be used in the printers. In the recent past, various commercial 3-d printers use computer aided (CAD) design for translating the design into three dimensional objects. The design can then be sliced into several two-dimensional plants, which can then instruct the 3-d printer where it deposit layers of materials. Therefore, from the literature, finding specialty materials is not an barriers to the adoption of 3-d printing technologies.

		Statistic	Bootstrap[a]			
			Bias	Std. Error	95% Confidence Interval	
					Lower	Upper
N	Valid	8	0	0	8	8
	Missing	0	0	0	0	0
Mean		2.6250	-.0375	.4998	1.6250	3.5000
Std. Deviation		1.50594	-.15187	.25684	.54612	1.76777

a. Unless otherwise noted, bootstrap results are based on 80 bootstrap samples

Table 12. Analysis question 26 (table of author).

7.4.2 Barriers to the use of 3-d construction printing

The study analyzed various obstacles to the use of 3-d printing industry. The results were provided in the form of question analysis for each indicator. As shown in the tables below, it was realized that high printer cost is an obstacle in the use of 3-d printing in the construction industry. That means that high printer costs were one of the barriers that were preventing effective adoption of 3-d printing in the construction industry. Therefore, the first step in as far as encouraging people to apply and capitalize on the technology is by addressing cost issues. Despite the fact that the technology is still new in the Netherlands, inability of stakeholders in the construction industry to meet the high costs of printers makes adoption more challenging. The second survey prompt implies that immaturity of printing partners is a significant barrier that prevents the adoption of 3-d printing in the construction industry. However, suspiciousness about the effect of immaturity of printing partners is there. However, it is not that significant, and that measure should be put in place to find lasting solutions to other challenges.

The fact that the study participants thought that unclear regulations was a stumbling block towards the adoption of the technology implies that responsible authorities including the government are lagging behind in adopting rules and incentives that promote the use of 3-d printing. However, the initial sample (before bootstrapping) never believed unclear regulatory obstacles to be a significant barrier to the adoption of 3-d printing in the construction industry. However, that does not mean that unclear regulatory issues should not be addressed. It means that the government of the Netherlands should promote the establishment of even better laws that can make the adoption of the technology as easy as possible. This piece of finding is essential because it encourages the Netherlands to continue in its course of providing clear laws and at the same time find a lasting solution that can be used to provide a platform for dealing with the housing supply crises that are seemingly not meeting demand.

Question 18 and 19

The fourth survey prompt (question 18) was: I believe that the inability to create larger structures is an obstacle in the use of 3-d printing in the construction industry. It was concluded that the participants in the study believed the inability to create larger structures to be a significant barrier to the adoption of 3-d printing in the construction industry. As such, inability to come up with larger structures was an issue of concern that was making the adoption and use of 3-d printing technology in the construction industry to be more difficult (see table 13 for anaylsis).

	Statistic	Bootstrap[a]			
		Bias	Std. Error	95% Confidence Interval	
				Lower	Upper

N	Valid	8	0	0	8	8
	Missing	0	0	0	0	0
Mean		3.2500	.1234	.7309	1.7500	4.8639
Std. Deviation		1.98206	-.14465	.31685	1.04322	2.32609

a. Unless otherwise noted, bootstrap results are based on 80 bootstrap samples

Table 13. Analysis question 18 (table of author).

The fifth prompt (question 19) was: I believe that the high cost of printed structures is an obstacle in the use of 3-d printing in the construction industry. That means that high costs of printed structures form part of the main challenges that make the adoption of 3-d printing in the construction industry problematic (see table 14). Therefore, it was concluded that the participants in the study believed the high cost of printed structures to be a significant barrier to the adoption of 3-d printing in the construction industry. As initially predicted, this is not a surprise at all because issues of costs have always been the main stumbling blocks towards technological adoption and implementation in different industrial sectors across the world.

		Statistic	Bootstrap[a]			
			Bias	Std. Error	95% Confidence Interval	
					Lower	Upper
N	Valid	8	0	0	8	8
	Missing	0	0	0	0	0
Mean		3.3750	-.0406	.5726	2.3750	4.4926
Std. Deviation		1.68502	-.10540	.31231	.75980	1.99513

a. Unless otherwise noted, bootstrap results are based on 80 bootstrap samples

Table 14. Analysis question 19 (table of author).

7.4.3 Commercial Viability, insufficient and successful projects, architect/designer preparedness, and Difficulty of transporting Printers, and technology interruption risk

Statistics

		Statistic	Bootstrap[a]			
			Bias	Std. Error	95% Confidence Interval	
					Lower	Upper
Mean	Q20	3.3750	.0531	.5852	2.1287	4.6250
	Q22	3.7500	.1516	.5624	2.7537	4.8750
	Q23	4.1250	.0781	.4926	3.1250	5.2463
	Q24	3.2500	-.0312	.6394	2.0037	4.6213
	Q25	3.2500	-.0266	.6484	1.7574	4.6213
Std. Deviation	Q20	1.76777	-.16509	.37037	.84047	2.32235
	Q22	1.83225	-.10866	.29227	.99860	2.25198
	Q23	1.55265	-.19290	.44369	.51805	2.16309
	Q24	1.83225	-.23109	.32193	.88729	2.26290

Q25	1.90863	-.16611	.34810	.51755	2.07020

a. Unless otherwise noted, bootstrap results are based on 80 bootstrap samples

Table 15. Analysis question 20-25 (table of author).

From the tabular analysis shown in table 15 above, only question 24 in the original sample shows the uniformity of the respondents on the fact that the difficulty of transporting 3-d construction printer for on-site use is an barriers to its application. There are various factors that could affect the transferability of the printer such as weight and measurements of the 3-d printer, accessibility of construction site, and the propensity of transporting prefab components and compartments. However, an extrapolated sample analysis shows that some commercial viability, lack of sufficient and successful products, architect/designer preparedness, and technology of interruption affects the use of 3-d printers in the construction industry.

From the interviews, most of the participants (70%) expressed their views about the costs associated with the adoption of 3-d printing, including insulating costs. The interviewees agree that 3-d has been successfully used in functional integration, however most of the uses are still not proven due to low rates associated with accepting the technology. About costs, the interviewees, just like the sample surveyed, expressed concerns that the it will take considerably time before 3-d printing will be more cost effective to print basically a standard straight wall instead of the conventional simple work forms. Equally, 3-d has the prospects of transforming the built environment and even the business model of a companies (as noted by 6 of the 9 interviewees). However, in the domain of cementitious materials, including outer walls, the interviewees expressed concerns that the change to the business model will not be as disruptive as initially anticipated. For instance, the promise that an architect can directly translate data from a 3-d model to build a construction is yet not possible, even with the use of robotics. Another point of concern that was noted was reinforcement. The study realized that reinforcement is one of the biggest challenges when talking about concrete extreme 3-d printing or added extra concrete to technologies in general.

7. Conclusions and Discussion

This section gives an overview of the results of the study and assesses if the objectives of the study were met. The study realized that the adoption of 3-d printing technology to the construction industry has faced several hurdles, including costs issues, readiness of the construction industry, high printer costs, concerns about commercial viability, customer support among other indicators. When comparing the experience and the likelihood that an individual should have knowledge of 3-d printing technology in the construction industry, the study failed to realize significant correlations. It follows that the construction industry has lagged behind in adopting sustainable technologies. When comparing questions 4 and 5, the objective was to realize some form of correlation between experience in the construction industry and knowledge of 3-d printing. The construction industry is generating a vast amount of waste and progress towards sustainability is significantly slow, at least as realized by the analysis. However, the complexity of the supply chains in the construction industry makes green management interventions to have considerably low-impact. Construction projects often involve thousands of various companies, making it highly unlikely to ensure a sustainable approach is implemented in the whole work process. However, from the study, number of participants indicated that disruptive technologies, herein a case example of 3-d printing technologies, can potentially revolutionize the way products are designed and manufactured, fundamentally altering the structure of supply chain networks. As backed by analysis, a significant portion of the interviewees indicated that the 3-d printing technology can potentially help the construction industry to be cleaner and considerably sustainable.

The table below, table 16, is a comprehensive analysis of all the study questions. For some of the indicators, even without a bootstrapped sample, the respondents readily identified them as potential barriers to adopting 3-d printing technology in the construction industry.

		Statistic	Bootstrap[a]			
			Bias	Std. Error	95% Confidence Interval	
					Lower	Upper
Mean	Q13	2.8750	-.0375	.4922	1.8787	4.1213
	Q14	3.5000	.0063	.5399	2.5000	4.6213
	Q15	2.5000	.0234	.5699	1.3824	3.9926
	Q16	4.3750	.0766	.5177	3.3787	5.3750
	Q17	3.6250	-.0531	.5089	2.5037	4.5000
	Q18	3.2500	-.0641	.6233	1.8787	4.4926
	Q19	3.3750	-.0109	.5570	2.5000	4.6176
	Q20	3.3750	-.0125	.5463	2.3750	4.6213
	Q21	3.3750	-.0781	.4970	2.2574	4.2500
	Q22	3.7500	.0344	.5907	2.3824	4.9963
	Q23	4.1250	-.0031	.4769	3.1287	5.1213

	Q24	3.2500	-.0734	.5652	2.0037	4.3713
	Q25	3.2500	-.0797	.6004	1.8750	4.3713
	Q26	2.6250	-.0688	.4660	1.5074	3.7463
Std. Deviation	Q13	1.55265	-.15626	.26236	.54341	1.80654
	Q14	1.69031	-.10363	.27535	1.06443	2.03101
	Q15	1.77281	-.16592	.45880	.52317	2.32609
	Q16	1.59799	-.17869	.45215	.70711	2.20194
	Q17	1.76777	-.07951	.27186	1.03586	2.12132
	Q18	1.98206	-.16303	.26354	1.24968	2.29518
	Q19	1.68502	-.13822	.32463	.74671	2.13809
	Q20	1.76777	-.11887	.35245	.88729	2.26779
	Q21	1.68502	-.12850	.26474	.99103	2.13492
	Q22	1.83225	-.10476	.33643	1.06066	2.47046
	Q23	1.55265	-.10406	.43292	.52120	2.19801
	Q24	1.83225	-.15760	.30259	1.06904	2.32331
	Q25	1.90863	-.10399	.21201	1.30931	2.13809
	Q26	1.50594	-.12892	.27191	.83452	1.90694

a. Unless otherwise noted, bootstrap results are based on 80 bootstrap samples

Table 16. Cumulative analysis of questionnaire (table of author).

The first question assessed the costs of purchasing a 3-d printer which can print outer wall components and associated paraphernalia. In the study, the participants expressed concerns about the exorbitant cost of a 3-d printer. A statistical analysis of the cost question is shown in table 17 below.

		Statistic	Bootstrap[a]			
			Bias	Std. Error	95% Confidence Interval	
					Lower	Upper
N	Valid	9	0	0	9	9
	Missing	0	0	0	0	0
Mean		3.2222	.0042	.5442	2.2255	4.6634
Std. Deviation		1.78730	-.12810	.25055	1.00275	2.12766
Skewness		.418	.001	.822	-1.582	2.396
Std. Error of Skewness		.717				

a. Unless otherwise noted, bootstrap results are based on 80 bootstrap samples

Table 17. Analysis question 13 (table of author).

From table 17, the initial 9 participants failed to reach a consensus about the cost concerns of acquiring a function 3-d printer; however, after extrapolation of the results, it is evident that a higher sample size would have considered cost a barrier to adopting 3-d printing in the built environment. Even for the interviews, the interviewees expressed concerns about the costs of acquiring a functional 3-d printing machine. Consistent with the findings, interviewer 1 indicates that the costs of acquiring and maintaining a 3-d printer can be outside the financial scope of some companies, especially start-up construction companies. Other associated costs include warranties, services agreements, maintenance, power consumption, wastage, and post processing. Despite the fact that the technology is still new in the Netherlands, the inability of stakeholders in the construction industry to meet the high costs of printers makes adoption more challenging. The first step in as far as encouraging people to apply and capitalize on the technology is by addressing cost issues. By doing so, firms and individuals including architectures who work in the construction industry can have the morale of encouraging the application and adoption of the technology.

While evaluating the effect of immaturity of printing partners as possible barrier towards the adoption of 3-d printing in the construction industry, the findings indicate that immaturity of printing partners was not a significant barrier preventing the adoption of 3-d printing in the construction industry. However, for an extrapolated sample size, immaturity of printing partners becomes an issue of concern in the adoption of 3-d printing techniques in the construction industry. Regulation considerably affects markets, especially through tariffs, governmental interventions, and incentives. While considering the implications of tariffs, the study realized that the smaller sample (original sample of 9 respondents) failed to consider regulation as a barrier to the adoption of 3-d printing technology in the built environment. As shown in the exhibit above, only 8 participants respondent to the question. A mean value of 3.6 was achieved against a threshold value of 4.

For an extrapolated analysis using a sample of 80 respondents, the study realized that a larger sample size would have considered regulation as an obstacle to adopting 3-d printing technology in the construction industry. An extrapolated result is shown in the cumulative analysis of the questionnaire, with a mean of 4.87 (95% CI). However, that does not mean that unclear regulatory issues should not be addressed. It means that the government of the Netherlands should promote the establishment of even better laws that can make the adoption of the technology as easy as possible. As a country, the Netherlands is yet to find a lasting solution that can be used to provide a platform for dealing with the housing supply crises that are seemingly not meeting demand. Therefore, the fact that the study participants never thought that unclear regulations was a stumbling block towards the adoption of the technology implies that responsible authorities including the government is in the right track in as far as the adoption of the technology is concerned and as such efforts aimed at establishing a convenient adoption environment should focus more on other challenges in the construction sector at large. While trying to establish whether the inability to create larger structures was one of the obstacles that made the adoption of 3-d printing technology difficult in the construction industry, the results justified that according to the study participants, inability to come up with larger structures was an issue of concern that was making the adoption and use of 3-d printing technology in the construction industry to be more difficult. Thus, considering that we are trying to evaluate these barriers in the context of the Netherlands, it can be argued that addressing the issue of inability of the right stakeholders to create larger structures will provide a remarkable foundation for developing a lasting solution.

Equally, high costs of printed structures form part of the main challenges that make the adoption of 3-d printing in the construction industry problematic. This is not a surprise at all because issues of costs have always been the main stumbling blocks towards technological adoption and implementation in different industrial sectors across the world. In other words, there are many industrial sectors that should making tremendous advances through technological adoption, but are unable to do so because of cost related concerns. Hence, it will be important for experts in the industry and more importantly, innovators to consider redesigning the technology even further to make it cheap and convenient for individuals and companies that operate in the construction industry. The analysis further shows that lack of commercial viability is a major stumbling block that was making the adoption of 3-d printing in the construction industry more challenging. Because creation of a lasting solution to the problem is vital, stakeholders in the field who are in the capacity of impacting commercial viability should look at the root cause of ineffectiveness and provide answers. In retrospect to that, findings of this research demonstrate that one of the areas that should be accorded a high level of attention was commercial viability because it is dragging apparent adoption of 3-d printing technology in the construction industry behind. Equally, as shown in the inclusive table, customer support is another significant barrier to adopting 3-d printing technology.

It was further noticed that insufficient successful examples are an obstacle in the use of 3-d printing in the construction industry. Therefore, it was concluded that the participants in the study did believe insufficient successful examples to be a significant barrier to the adoption of 3-d printing in the construction industry. The study equally noticed that technology interruption risk is an obstacle in the use of 3-d printing in the construction industry. The participants think that technological interruption is an issue of concern that should be addressed soon enough because it is making the adoption and implementation of 3-d technology in the construction sector more problematic. If anything, more experts and resources should be set aside to enhance the capability of dealing with the barrier in the future.

Interview findings from the participants provided more insights about the gravity of the issue of 3-d printing and its adoption in the construction industry. While trying to find out how FLAM (Fungal-Like Adhesive Material) can be integrated successfully into a 3-d printed cementitious outer wall as well as things to do with insulation effects and cost of such an approach, interview results showed that attention is being redirected at printing concrete and that FLAM is a new material that can potentially be added or a replacement to the additives or additional material. The actual cost being incurred with the use of FLAM is the cost that is involved in replacing sand or other materials. Furthermore, insulation implication relied on FLAM itself. FLAM is some kind of a buffer and that increases insulation value because it has the same structural properties or features like that of materials that look like wood (Sanandiya, 2018). However, in the Netherlands, that will mean that the wall element should be comprised of a huge thick outer wall. FLAM can assumable used like a conventional insulation that one might need for materials like bio-pearls. The material has significant effect on the printability of a material in relation to probability because one has to end up with a printable material. Interview results also saw the interviewees citing FLAM as sustainable and a great way that people in the construction industry can utilize to help reduce carbon emissions. Part of the information that was shared to the interviewees was that the cost of FLAM is less than 2$/kg, similar to commodity plastics and is 10 times lower than the cost of common filaments for 3-d printing. This material can also be used to 3-d print large structures for objects such as an outer wall' (Fernandez, 2019). Thus, according to the interviewees, it is possible to create a passive structure with very well optimized to parametric insulation capabilities according to the latitude of the application. The same building, the same outer wall might be tailored for the particular climate condition zone by zone, climate by climate. Also, since FLAM is biodegradable, the deterioration time should be considered while the material is produced. However, this should not be considered as negative as such because of depreciation expense tax benefits it gives from an economical point of view. The cementitious material has been for a long time something quite far away, for instance, from machines. Engineers used to talk about concrete and not talk about the raw materials behind. There are a lot of entities who might be intrigued to promote the realization of outer walls recycling materials and the second-hand material which was a quite unheard possibility until the augment of 3-d printing. In retrospect to the scalability of this material, there is potential to scale this product. However, none of the interviewees heard of FLAM before, and they did not know yet on how it would act in the real world. This is no surprise because the research is published at the end of 2018. However, one interviewee did have valuable knowledge of other biodegradable and ecologically sustainable materials. According one interviewer PETG (+-$18,-/kg), PVDF (+-$18,-/kg) and ASA (+-$4,5/kg) are potential polymer based 3-d printing construction materials. These materials are finer to print with than cementitious materials, have better design capabilities than conventional materials, are sustainable and 3-d printed houses is a possibility. However, 3-d printing high rise buildings, which has a higher building density than family houses, is currently not possible with polymers and therefore it is currently far less scalable than cementitious materials. Moreover, it can be concluded that there is a practical knowledge gap of FLAM (and other polymer based materials), the articulation of competitive strength is not thoroughly considered yet and there exists a lack of standardization of FLAM. Therefore, it is clear that these factors act as barriers to the scalability of FLAM (Coutu, 2014; Nielsen et al., 2018).

Other than questionnaire results, the interview results also provided a great basis for exploring the innovative capacities of 3-d printing with reference to the function and design of a cementitious wall. According to them, 3-d printing allows people in the construction industry to design wall elements differently from the design of conventional walls. Also, 3-d printing is important because it provides different designing methodologies such as parametric modeling. In other words, the technology does not actually design, but rather script algorithms that can be applied at different construction levels. These algorithms can then be used to aid the designing process and that one can possibly end up with more than 400 million different kinds of shapes per day, which is a great innovation. Other than process innovation, interview findings also showed that individuals should also be socially innovative to get the best out of 3-d printing technology. The technology is based on three aspects including social innovation, process innovation, and technical innovation. In the meanwhile, the interview results also made it clear that 3-d construction printing is commercially feasible implying that its use can enable construction companies to have a better chance of addressing construction costs. Generally speaking, the cost per product for 3-d construction printing is decreasing enormously. With the technology, there is also the choice for off-site and on-site printing objects which can be a value proposition. However, current cementitious 3-d construction printers take a fast amount of energy which can be an issue for on-site fabrication. In conventional construction, the failing costs are between 5 and 25%. When you translate this to the consumer side, then the consumer will get an architecture which will fit better to its needs on the demanded functionality. Scalability is equally important for the 3-d printed product as for the material itself.

The ways in which 3-d printing technology affects business models was also an important area of discussion in the interviews. According to the interviewees, many companies operating in the construction industry are considering the adoption of 3-d printing technology lately. These companies are interested in different models. A great example is a company which developed a printing technology in collaboration with partners. Just like the general contractor, these companies design, engineer, print, produce and sell those model elements. Another company focuses on developing 3-d printers and sells them to companies but it is not their focus. This company operates with its technology department who assist in printing, designing and engineering entire buildings including walls, floors and other parts. In certain countries where companies are not entirely conversant with 3-d printing technology, the company in question has been providing guidance at different applicability levels. As at now, 3-d construction printing is used for customized and complexed design. Hence, if further developed and the learning curve is as well enhanced, eventually 3-d construction printing will be used for simpler designs. This will be possible in the near future. Possibly when there is more competition, which suggests that simple forms are already commercially feasible when the learning curve is enhanced.

According to the interviewees, 3-d printing technology is more of an integrated design solution. The innovation merges design engineering and production into a single system. Also, the technology is user friendly and generally effective in terms of applicability. In addition, the technology makes engineering designing and production fast and convenient. However, some interviewees like interviewee 1 stated that if another technology that appears to be better than 3-d printing emerges, it will be embraced automatically. In terms of being used for innovative purposes, interview findings demonstrated that the technology is being integrated with the robotic system and other technologies to enhance effectiveness. Robotics means right software. Additive manufacturing is generally requiring methods to slice and to process the design for the additive manufacturing. Nonetheless, part of the main concerns is that many architects working with conventional companies lack experience as structural engineers and thus, they prefer doing things conventionally. The most 3-d construction printed wall typologies are made of cementitious materials which is a conventional building material. The questions therefore must be, if we should develop new technologies with new advanced building materials rather than with conventional building materials. Construction projects that are coordinated by people who work with conventional companies are not only time-consuming; they are also costly. A majority of these firms will argue that 3-d printing cannot be fully adopted in the near future because it is very expensive. However, solution lies with the willingness to increase information within production, engineering and design processes.

Interview results also proved that despite its capabilities, the knowledge gap on 3-d printing technology is a critical barrier that makes its adoption and implementation problematic. Barriers that are associated with the use of 3-d printing for the design of cementitious outer wall can be addressed by hiring structural engineers and architects in house as well as promoting awareness on the technology. Consequently, 3-d printing technology has changed the conventional construction approaches in multiple ways. For instance, it is now possible to model building designs through an integrated digital value chain rather than going for sketches. Lack of proper standardization has made 3-d printing difficult to adopt because some people are not sure whether the technology is safe or not, or even aesthetically justified since it is different. In fact, some regulations such as European regulation can only allow the technology to be used with assurance of the designs that are being tested. That means that construction companies might fail to get approval or permit to

coordinate construction projects at the municipality level. In the meanwhile, technology has been identified as the fundamental solution to many challenges that are being faced in the construction industry including barriers of typology. One interviewee stated that because their building was aesthetically different than conventional construction, it caused the most significant delay in the whole process due to strictness of the municipality. Technical approval was easy in their project.
According to the interviewees, the adoption and implementation of 3-d printing will have multiple advantages. The algorithms will manage the process and not people. People will go from executive roles to coordinative roles. In terms of disintermediating capability of 3-d, the interviewees noted that the robot is not so much the reason but a mandatory cause for the parallelization. Moreover, 3-d construction printing is not the one method. Instead, it is a method in the reign of digital fabrication and that with robots, there is a wide range of possibilities. 3-d construction printing is a scalable product that is fast and affordable. The material is relatively affordable meaning that adopting it will make it more competitive compared to conventional methods. 3-d construction printing itself in combination with the use of integrated design algorithms is innovative. You can make different walls and different shapes thus making construction process generally easier even in the most difficult areas to build such as swampy areas or places where the soil is soft. You can build better outer walls, but also better fundaments with a 3-d construction printer because you don't directly put the fully weight on it. With the technology, it is possible to create more appealing buildings without the extra costs. The 3-d printing is excellent to create very complex shapes with the capability of ventilation or insulation or heat dissipation because the process of the possibility to create a skin and to create a membrane much more tailored for the environment. There is confidence in that 3-d construction printing is altering the construction value chain in the near future, but mostly it is part of a parallel value chain. The most interesting thing about large scale 3-d construction printing is the fact that you can use materials as a way of adding functionality. Normally this is done by layering, so making, stacking additional materials on top of each other to create certain kinds properties like insulation, strength, water resistance, all that kind of elements.
In retrospect to the scalability of 3-d construction printing a cementitious outer wall, it has potential, but a whole product has not been reached yet which is also proven to be scalable. It is clear from the statistical analysis that most of the barriers from the literature review are still existent. The interesting part is, that the interviews showed there is potential. It is suggested that this potential

can be discovered in the combination of the (3-d printing) technologies. Therefore, it is suggested that 3-d construction printing can become scalable if the proposed barriers and the undiscovered barriers in this thesis are overcome. The undiscovered barriers mostly can be found in 3-d social innovation, process innovation and technical innovation for the 3-d printing construction technology as for the material itself. A fully automated and integrated process to 3-d print a wall typology is needed. In this case, this would be the typology 'advanced reinforced cementitious wall' on page 53. 3-d construction printing project examples of this typology are 3DCP (TU Eindhoven), Thin Folded Concrete Members (ETH Zurich), Shotcrete 3-d printer (TU Braunschweig). It is suggested that the 3DCP project has the most potential in terms of scalability in the shorter timeframe.

However, interviewers also stated that this has to do with finding the 'hot zone' in business model scalability. Amongst these examples, the 3DCP printer example is the simplest version; which is a good thing in terms of scalability. Amongst the 3-d construction printer itself, it is suggested that this 'hot zone' is a fully integrated digital chain. Within this chain, people will go from executive roles to coordinative roles. To contribute to the solving of the research problems, scale must be attained and therefore, large sums of investments must be attracted.

Regarding the five scalability aspects of Nielsen et al. (2018), the first signs of new distribution channels are there (mostly digitalised and integrated channels), 3-d construction printed businesses can be limited by traditional capacity constraints such as employment scarcity within the built environment. It was clear through the interviews that capital investments are outsourced to partners who effectively became participants in the business model. Also, it was clear that customers and other partners play multiple roles in the business model. Lastly, the interviews did not show that there is a clear platform model, where competitors may become customers, which is essential in terms of scalability.

Interviews showed there is a commitment to grow in some companies. However, a lot of technologies are in the research phase at universities, and it was clear from the interviews that most of the researcher did not know about business model innovation or scalability. It would help to get researcher more motivated on the entrepreneurial aspect of things such as workshops from incubators that have close contact with the universities, which brings it to the third aspect of broad management skill set and useful mentorship which is a critical aspect to the scalability of a business.

Therefore, the learning curve must be enhanced, and the solution lies in the willingness to increase information within production, engineering and design processes.
Moreover, there is a lack of proper standardisation, which is another critical aspect in terms of scalability issues (Coutou, 2014). Also, the regulatory difference and digitalisation per country makes it very hard to operate and limits the scalability of 3-d construction printing. Currently, it is clear which material is the right material in terms of scalability; Cementitious materials. However, in the interviews was shown there are to schools of thought which can cause a technological interruption risk on materials. The school of thoughts can be described in terms of (1) 3-d construction printing with conventional materials or (2) with totally new materials. The former makes sense from a scaling point of view, due to the knowledge people have that can design, engineer and construct the material. The latter is more logical from a holistic point of view; new technology needs a new way of thinking, and therefore, it needs new printed materials which suit better to the needs of the client. However, the latter is less scalable on the shorter term since there is still a significant knowledge gap of the new materials such as FLAM or the use of polymers.
In retrospect to the adoption of 3-d construction printing with cementitious materials, it is clear we still need to bridge the 'chasm', and by focussing on the posed scalability issues, we can potentially bridge the chasm. From the results and findings, it is suggested that the major stumbling block that prevents the adoption of 3-d printing in the construction industry is lack of large groups of people who can commit themselves to push the technology forward. Most assumedly, the reason for this is lack of financial incentive to necessitate the fostering of knowledge on how 3-d printing works and how it can be applied in the construction industry. Therefore, is it suggested that the posed innovators dilemma of Christensen (1997) remains valid for the gross of the companies. In addition, only if these issues are be overcome then 3-d construction printing will assumedly contribute to the resolving of climate change, the depletion of natural resources and socio-economic factors (Moore, 2014).

8. Recommendations

- Significant and non-significant barriers that affect the adoption of 3-d printing in the construction industry should be evaluated further basing on findings of this study and a line of distinction created between the two for prioritization purposes.
- Further research should be conducted to provide more insights and information on how 3-d printing works and how it can be adopted in the construction industry with ease.
- Stakeholders in the construction industry should collaborate where possible to necessitate the success of adoption of 3-d printing technology in the sector.
- Technological barriers should be addressed to pave the way for effective adoption of 3-d printing in the construction sector.
- More research is needed to the scalability of materials and 3-d printing technologies involved.

Reflection

I had a very engaging research experience. I started the research by reading more about 3-d printing and its adoption in the construction industry. I did so because my goal all along was to come up with a reliable and valid product that can be used to solve some the pressing concerns that are being experienced in Netherland's construction industry. Important conditions for me where that the product would be scalable and commercially interesting. In the meanwhile, I used questionnaires and interviews to find possible answers to my research question. I structured the research questions basing on the respondents that I was targeting. The good questions that I came up were simple and covered important areas that formed the basis of this research. After reaching out to the study participants, I noted that finding the right number or targeted number of participants (9 participants) was somehow challenging. I merged the two interviews that I had initially developed into one interview before carrying out the interviews. Initially, I had developed a point of departure to help me formulate research goals and more importantly, ensure that everything was on the right track.

Despite reaching out to 10 architects with potential experience in 3-d printing technology, only 2 were willing to participate in the questionnaire whereas the other 8 stated that they were too busy. Apparently, the 2 respondents were not entirely experienced about 3-d printing technology. However, I happened to gather findings from 4 interview participants who identified themselves as researchers and architects with knowledge in 3-d printing technology. I decided to formulate as many questions as possible because the more the number of questions, the higher the chances of gathering more information on 3-d printing and its adoption in the construction industry.

The small pool of research made it difficult for me to engage as many participants as possible. After all, the response rate of the questionnaire was a bit disappointing. This is because the industry is small and therefore I took a risk. I am glad I listened to my supervisors and made the choice to conduct additional interviews. Nonetheless, I was lucky to have met real experts in the field of architecture who helped me carry out this research. I used phrasing technique to formulate my research questions. At the back of my mind I knew that with 3-d printing, it will be possible to get new forms of buildings that can serve housing needs of people of the Netherlands and at the same time promote environmental sustainability and effective use of materials. Hence, I even though many people are not entirely familiar with the technology, similar researches can play important roles in enhancing enlightenment in the sector. Technology has become part and parcel of human life in the modern world. Hence, I think it is high time that the same technology should be made commercially viable and scalable in the construction industry. Other than being profitable, my focus is to help ensure that product of 3-d printing technology can provide a basis for dealing with issues of socio-economic problems and inability to access quality housing, depletion of natural resources and climate change that is being accelerated by carbon emissions.

I measured the success of this research by comparing the conclusions that I made with my initial study expectations. Moreover, I evaluated the significance of this study by ascertaining the change the extent by which I was going to contribute to change in the construction industry by publishing this thesis and making it available for public access. I also understood that adoption of 3-d printing in the construction industry was going to affect various things that includes and are not limited to competition between firms, power, politics, and access to quality housing. Both the interview and questionnaire questions that I formulated to guide the documentation of this research were great and played their roles well. However, due to time restrains from my side the focus became on the qualitative part. Looking back, I would have liked to focus more on the scalability issues as I did not define the term scalability well enough for myself in the beginning, mostly because I was too focused on the barriers of 3-d construction printing itself. If I had focused more on scalability sources, in the beginning, it could have resulted in better conclusions and my research could have been better. Also, I would have like to be more critical since I am quite positive on 3-d construction printing. However, I tried my best.

I encountered several challenges trying to deliver my thesis. First, I had to rewrite the thesis basing on the comments on the P1 report. It was as well difficult for me to change the research angle after conducting further assessment on the technology subject of this research. This was mainly because I was very enthusiastic on the research approach that I had taken earlier on. The underlying need to switch gears quickly was also a presenting challenge. Nonetheless, this piece of reflection and critical assessment has provided me with different views and insights that I might have risked to lose after all.

Second, the novelty of 3-d printing as well as the limited literatures and studies that are available on the subject made the documentation of this study more challenging. The missing link was unavailability of RRI framework. Third, I solemnly understood that the foundation of conducting an effective and constructive research is beginning by asking the right questions. Hence, I had to spend a lot of time trying to figure out some of the possible questions that could help me find solutions to the research problem. It was difficult for me to phrase the main questions and sub-questions thereby limiting the general scope of my research study. Because of that, my main focus was on trying to have a coherent understanding of research problem first from where I used that to come up with questions that were in line with the research problem.

The interest that I had on the research subject made it difficult for me to limit the scope of this research. It was a challenge that I had to focus on and subsequently address the most critical findings of my study research. Switching gears and changing the research approach has improved my ability to sharpen and scope research studies. I remember having it difficult to proceed further after delivering my first P3 report. At the back of my mind, I knew that it will take another two months for me to complete my P4 report after handing in my P3 report. I also knew that I had a short time frame and that I had to push myself and remain focused to have it done. Nonetheless, things never turned out as initially planned because despite being too optimistic, I struggled to write and put everything together such that because of concentration concerns. This was a significant setback on my side because I did not have enough time for the P4 registration. After the Go for my P4 report, it was hard for me still to continue due to personal reasons. It was a relief that I passed my P4 presentation, which means I was close to my graduation. However, at the same time, I just wanted to move forward, and that was quite the challenge for me due to personal reasons. It was challenging to keep the overview and to connect my literature findings to my research results because I could only work a few hours effectively per day. I would have liked to evaluate my literature that I already possessed more thoroughly and draw better conclusions between the literature, the statistical analysis and the interviews. Also, I would have liked to refine the measures section amongst other sections. In retrospect to scientific relevance, I think my thesis is quite relevant in terms of the newness of the topic concerning barriers, adoption and scalability of 3-d construction printing. For me, it was hard to get the focus point of my thesis, that was a process on itself. I think it was good to use mixed-methods as a methodology, but in retrospect, I could have fine-tuned the research question and questionnaire better to scalability and adoption. On the other side, that is quite a risk because there are not so many people knowing about this subject. The dilemma's that I found was that I got the feeling that some participants were defending their 3-d printing business in terms of 'sales talks'. On the other hand, I can not prove this, but there must be a bias here. Unfortunately, I found out that there is a reflection format for this year. I have agreed with my supervisors that I could use the manual of the year that a started in, so I hope this is not an issue. I wished I had the time to spend more time on this and that I found this out earlier. On the other hand, I had to choose my focus point, and that was on finishing the thesis itself. It is a pity that I did not follow the format because reflecting gives me a good feeling after project delivery, and I would have like to learn from it in a more focused way. Despite these ups and downs trying to meet deadlines and struggling with personal issues, I remained positive and relaxed as possible all the way through.

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