Witteveen + Bos

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The roadmap to standards for 3D concrete printing

Research on the interplay between technological and legislative developments

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PREFACE

Before you lies the dissertation "The roadmap to standards for 3D concrete printing". This report describes a roadmap that goes along all the phases that concrete printing can potentially go through in terms of regulation and legislation. For this, standards in the Eurocode are the dot on the horizon. However, since this is still in the distant future, the research, therefore, focusses mainly on standard development for the coming years. This research was commissioned by the digital construction department of the engineering firm Witteveen+Bos in Deventer.

The Digitial Construction department plays an important role in 3D concrete printing when it comes to ensuring structural safety. This makes it interesting for Witteveen+Bos to conduct an exploratory study into the future of regulations for concrete printing since the regulation process is now going through a thorough intensive process and requires a bespoke solution per municipality. What standard should be written down and by what kind of parties should it be picked up will be explained in this report.

During the research, Marijn Bruurs and Hans Laagland helped me a lot in finding the right information, contacts and defining an appropriate scope. In addition, both have taken plenty of time for me, often after office hours, for which I am very grateful. I also want to thank my supervisors from the University of Twente, Farid and Monik. For your feedback that helped me on the right track.

I also would like to thank all the experts who have been interviewed for this research, often with their busy schedule. I would like to thank Theo Salet, Simon Wijte, Rob Wolfs, Helen Kok, Jan Blaakmeer, Pieter Bakker, Maartje Dijk, and Arno Poels very much for the nice and very informative conversations I have had with you. This research never came to what it is now, without your contributions.

To my other colleagues at the Built Environment department: thank you for the daily support and the pleasant time at the company. My parents deserve a particular note of thanks: your wise counsel and kind words have, as always, served me well.

I hope you enjoy your reading.

Tom Diks

Deventer, July 5, 2019

Cover photo by 3Dprintedhouse, taken from https://www.3dprintedhouse.nl

ABSTRACT

The technology of 3D concrete printing (3DCP) is rapidly evolving over the past years. In a relatively short period, the technique has proven its first real civil project in the form of a small bicycle bridge in Gemert. As the technology becomes more mature and increases in technological readiness levels (TRL), other aspects within 3DCP become more relevant. An important aspect of what is still challenging for the innovative technique is legislation. Since the developments are still strongly in development and many research institutes are printing in its own manner and legislation is early to think about setting standards. Discrepancy research has been done to map where are still the challenges in order to reach a complete standard that covers every aspect. To set the first forms of pre-standards (that serves as handles for regulation), it is important to create a broad-based consensus. A uniform agreement should contain experts in the field of academic, industrial and governmental perspective. Also, since concrete printing deviates on almost every aspect, new additional standards should be written regarding concrete mix design, structural design, and execution design. All categories should contain some form of technical recommendation in order to ensure the quality of the printed structure. This research resulted in a roadmap that describes the safety phases for 3D concrete printing. The results of this study emphasize the need for standardization of scientific test methods, sharing knowledge and the will to work together. These points determine the speed of the development of regulation for 3DCP.

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DEFINITIONS AND ABBREVIATIONS

Definitions

Printed concrete	A concrete structure made in a digital manner by an extrusion process of filaments
filaments	A slender threadlike layer of extruded concrete
Mock-up	A model or replica structure, used for experimental purposes
Additive manufacture	The process of joining materials to make objects from 3D model data, usually layer upon layer.
Extrusion-based	Additive manufacture printing technique that makes use of a nozzle
Nozzle	A device designed to control the direction or characteristics of a fluid flow
Rheology	The branch of physics that deals with the deformation and flow of matter, the flow of liquids and the plastic flow of solids
Thixotropy	The property of becoming less viscous when subjected to an applied stress
Batch	Quantity of fresh concrete that is mixed in one cycle of operation
In situ	*In situ* - building a structure on site

Abbreviations

3DCP	3D concrete printing
DBT	Design By Testing
TRL	Technological Readiness level
EC	Eurocode
EB	Extrusion based
AM	Additive manufacturing
ULS	Ultimate limit state
SLS	Serviceability limit state

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1 INTRODUCTION

1.1 Problem description

Worldwide, the building environment is facing major challenges for the coming decades. Factors such as urbanization, energy transition, smart mobility, a growing lack of natural resources, climate change, an aging profession that are insufficiently complemented and the shift of urban economies from industry and services towards knowledge and creativity are a few examples of factors that will affect the building environment (McKinsey Productivity Sciences Center, June 2016). The construction industry is known as a quite conservative sector compared to the total economic productivity see figure 1.1.

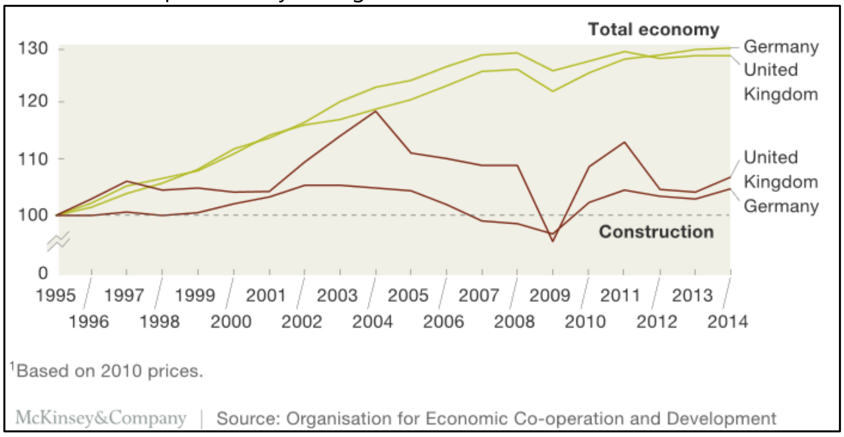

Figure 1.1: Productivity in the construction sector (McKinsey Productivity Sciences Center, June 2016)

research has shown that contractors have to build more than 3,600 buildings per day by 2050 (Statista, Autodesk, 2018). With these looming developments, the pressure on innovation is increasing in order to meet construction demand in the future. New more efficient methods need to be developed. Like we have seen in many other industries (Bos, Wolfs, Ahmed, & Salet, August 2016) (e.g. manufacturing and agriculture), the digital disruption could potentially become a game changer to meet these major challenges in the building environment as mentioned before. 3D concrete printing (also known as 3DCP) is a promising new building technique in digital construction. The technique requires less material, because you only print where it is structurally needed, creates less waste, because there is no need for formwork, simplifies the building logistics, because you can produce everything in a factory instead of in situ and reduces labor intensity in comparing to conventional building techniques, since the robot takes over most of the labor and finally reduces building time. For example, the US military printed 3DCP barracks in less than two days, which is a major reduction in building time compared to similar concrete structures. Still, this new way of building has some challenges to overcome in order to become a compelling construction alternative. One important challenge, for example, to overcome with 3DCP is legislation. Codes that prescribe for example which tests must be performed are not available yet. Without such standards, 3DCP won’t get out of its infancy. A detailed explanation of 3DCP can be found, for example, in "3D printing of concrete structures" by R.J.M. Wolfs (Wolfs R. , 3D printing of concrete structures, February 2015).

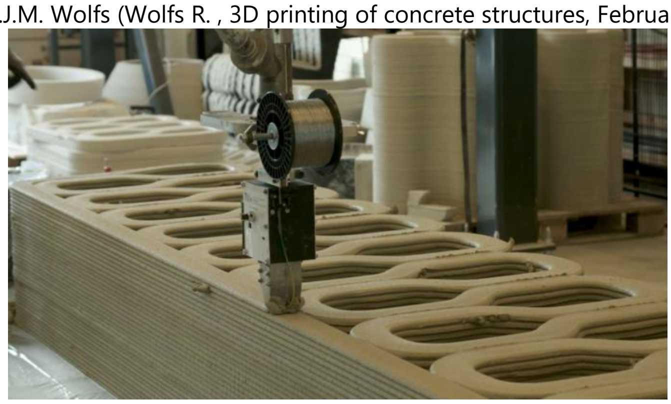

Figure 1.2: Example of 3D concrete printing (Bos, Wolfs, Ahmed, & Salet, August 2016)

1.2 Research aim and questions

The department Digital Construction from engineering company Witteveen+Bos is one of the pioneers when it comes to 3DCP and structural safety. Since safety regulations are closely linked to standards it is the wish from the company to get solid insight into the world of standard and regulation and how this can be developed for 3DCP. The problem statement is as follow:

To get 3D concrete printing out of its infancy, it is among other things necessary to develop standards. Currently, no exploratory research has been done into the possibilities and potential of possible standards for 3DCP.

Since Witteveen+Bos could benefit from standards for 3D concrete printing, it is, therefore, crucial to get a clear view of possible future alternatives. Since 3DCP and regulation is never set by an individual organization it is therefore important that every relevant stakeholder is identified. This leads to the following research aim:

To determine what phases are part of the transition to standards for 3D concrete printing in the Netherlands.

The problem statement and the research aim lead to the main question:

What steps need to be taken to achieve standards for 3D concrete printing in the Netherlands?

To be able to answer the main question, insight is needed on the state of the art regarding 3DCP and where there are still technical challenges. Also, Insight into standards is required to provide an appropriate recommendation. Therefore, the following sub-questions have been drawn up:

Q1. How is approval given for a new construction technique in the Netherlands?
Standards are often crucial for the building permit, and how this process normally goes is being investigated. Furthermore, it is also investigated how a permit process works if standards are absent.

Q2. How does a general new innovation develop?
For every innovation, it is important that standards are adopted in the long term. It is therefore good to understand how innovations usually develop and to determine when is the time designated to adopt standards. In this chapter the state of the art is determined to determine whether it is time for standards.

Q3. At what points does 3D concrete printing differ from regular concrete?
It is only necessary to develop a new uniform guideline on the aspects that deviates from the already existing standards and regulation. That is why the technical aspects of innovation are looked into. A division is also made to keep it manageable.

Q4. Which stakeholders have importance in 3D concrete printing, and who can take which steps?
In order to develop a clear view of the power and interest of every relevant party. A stakeholder analysis is therefore performed on a case study. This case study concerns a current 3DCP project in the Province of Noord-Holland where four bicycle bridges will be printed. Since permission is required in order to build and no standard exists yet, it makes this situation very relevant to use as a case study for the research.

1.3 Research methodology

Figure 1.3 shows the system used for this study. Displayed are the processes and the aspects that form input for the final recommendation. As can be seen in Figure 1.3, the process to form a proper recommendation consists of four parts.

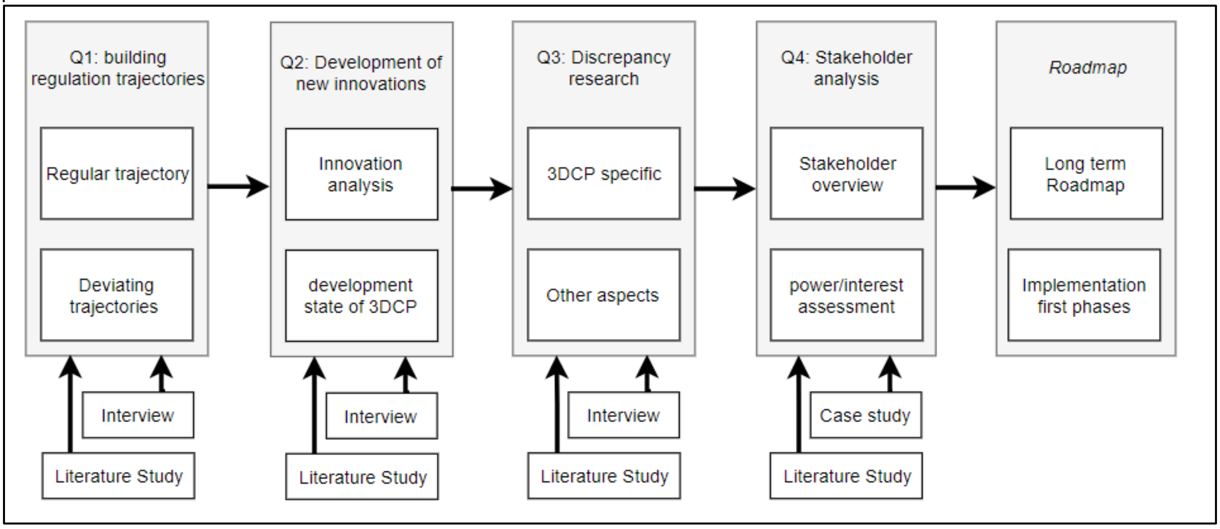

Figure 1.3 Research methodology

The first part describes how a building regulation trajectory works and what happens when no standards are present. This will be supported by interviews with the municipality and engineers who have to ensure safety. Also, a literature study on the current regulation trajectory and standard organizations is a method that contributes to this chapter and providing a conclusion on question 1. The next part will consist of an analysis of 3DCP where it will be divided into categories. A 3DCP flowchart to ensure safety will be drawn up based on literature and face validity checks during expert interviews. Then, a list is made of topics that consist of challenges for 3DCP to overcome in order to set standards: a discrepancy research. This research is compiled by literature and in-depth interviews with experts on developing 3DCP tests. This makes it possible to answer question 2. The third part will explain the development of new innovations. This is being supported by Interviews and literature. Interviews with innovation experts and literature on the recognizing of patterns in innovation in general. This will provide an answer for question 3. The last part consists of a stakeholder analysis that has been performed on a real-world case study in the Provence of Noord-Holland. This part will give a useful view of all relevant parties that have an interest in concrete printing and therefore in setting standards. Together with a Power-interest grid, it will be able to perform an answer on question 4. A recommendation can then be formed from all findings. A recommendation consisting of two parts: a roadmap that defines what the future phases of safety regulation for 3DCP will be and an implementation of the first phases.

1.3.1 Literature

A literature study has been done in order to provide a foundation for the direction of the research, what has been investigated and what not. The literature research contributed to the identification of the right problem statement and setting research boundaries i.e. creating a suitable scope. For this study has been searched for papers with a technical and a legislative perspective relevant for 3D concrete printing. Very few research has been done on the intersection of both cases. There is literature on regulatory developments of new innovations outside the construction sector (e.g. Drones). However, these regulatory processes are very different, because they must take completely different safety aspects into account. Often, regulatory processes are also initiated and set up by the market. Characteristic of this is that they do not appear as scientific publications. However, there was often sufficient literature for the sub-questions. Literature with regard to a building regulation process, the development of a new innovation, 3DCP and all deviations and finally literature with regard to the stakeholder analysis. The literature that has been used as knowledge production for this report is mentioned when it has been used. Finally, there is a overview of all literature used in the references.

1.3.2 Interviews

Since this scientific research is based on a non-epistemic purpose, it is important to do proper observations. A crucial method to do a profound recommendation for a potential roadmap is to do in depth-interviews. Of course, it is important to give objective advice that suffers a little from any bias. Therefore, an attempt is made to interview such a varied selection as possible. People from every perspective in the triple helix model (governmental, industrial and academical perspective) (Triple Helix Research Group, Juli 2011), are, therefore, interviewed. The interviews had two purposes: production of knowledge (knoPro) and validating certain choices to justify their own produced results (Sargent, 1996). An overview of all persons interviewed together with the corresponding function, organization and interview topic can be found in table 1.1. the findings of the interviews have been incorporated into the research. For each interview, it is indicated at which chapter the interviews are of added value. The structure of the interviews can be found in Appendix A.

Table 1.1: overview of expert interviews

Name	Title	Function	Organistion	Date	Subject	Chapter of findings	Type of interview
Simon Wijte	prof.dr.ir.	full professor Sustainment of Concrete Structures	Eindhoven University of Technology	26-4-2019	What are standards and how do they work	Chapter 2	KnoPro
Marijn Bruurs	MSc.	Consultant Digital Construction	Engineering Company Witteveen+Bos	6-5-2019	How to write a good standard	Chapter 2 & 3	KnoPro / Validation
Hans Laagland	ir.	Manager Digital Construction	Engineering Company Witteveen+Bos	6-5-2019	What sort of standard categories exist	Chapter 2, 4 & 5	KnoPro / Validation
Jan Blaakmeer	Phd.	manager Research & Development	Mortar producer Saint-Gobain Weber Beamix	24-5-2019	3DCP material and regulation	Chapter 4 & 5	KnoPro
Theo Salet	prof.dr.ir.	Dean of the Faculty of Architecture	Eindhoven university of Technology	27-5-2019	The future of 3DCP regarding standards	Chapter 3 & 5	Validation
Maartje Dijk	Msc.	Structural Engineer	Engineering Company Witteveen+Bos	7-6-2019	The role of standards research commission	Chapter 2 & 5	KnoPro / Validation
Rob Wolfs	Phd.	PhD Student 3D Concrete Printing	Eindhoven university of Technology	13-6-2019	How to design tests for 3DCP research	Chapter 3 & 4	KnoPro / Validation
Pieter Bakker	ir.	Project leader 3D-printed constructions	Construction company BAM	13-6-2019	Current 3DCP challenges	Chapter 4	Validation
Helen Kok	Msc.	Structural Engineer	Eindhoven municipality	13-6-2019	The role of municipality with new building innovations	Chapter 2	Validation
Theo Salet	prof.dr.ir.	Dean of the Faculty of Architecture	Eindhoven university of Technology	19-6-2019	Ensuring safety when no standards exist	Chapter 4	KnoPro
Arno Poels	Msc.	Structural Engineer	Engineering Company Witteveen+Bos	21-6-2019	How to engineer a 3DCP structure	Chapter 4	KnoPro

1.3.3 Case study

The role of the case study in the research is to investigate the regulation method used in this process. Because a regular trajectory for 3DCP does not exist yet, the case study in the research can therefore really contribute to the results that provide more insight into a future roadmap. For the case study, Several in-depth interviews with people from the industry, government and other stakeholders are conducted to understand what the need of every stakeholder is to give implementation to 3DCP regulation.

'Circular economy' and 'smart industry' are of paramount importance for the Province of Noord-Holland (Noord-Holland, 2019). These goals serve as an incentive to work with 3D concrete printing since 3DCP fits perfectly in that vision as explained in the introduction. Also, this project is a good example of a project which involves the triple helix (Triple Helix Research Group, Juli 2011). The triple helix refers to a set of interactions between academia, industry, and governments, to foster economic and social development. The project is currently in an early phase. More about the case study can be found in chapter 5.

1.4 Scope

To keep the research manageable, it is important to determine which boundaries research is done. The scope will focus on regulations for:

- 3D concrete printing
- Extrusion-based print technique (see 'Definitions')
- National regulation for the Netherlands
- Regulation within the construction sector
- Structural construction
- All 3DCP structures (e.g. bridges and houses)

1.5 Research relevance

A literature review has been done within the scope of concrete printing. These studies often focus on the printing process itself, but rarely is it about implementing into legislation, as mentioned earlier. Research on how legislation can regulate new building techniques is also scarce. Research on this intersection will therefore certainly be relevant for the future of concrete printing.

Scientific relevance

The scientific relevance in this research lies in, mapping all sorts of pre-standards with new construction methods. By mapping all existing technical recommendation instruments and the associated advantages and disadvantages, the research can have added value for future scientific research on selecting a suitable intermediate phase for other new building methods. Therefore, this research can contribute to streamlining regulation for other new building methods in the building environment.

Societal relevance

To meet the large promises that 3D concrete printing seems to be able to fulfil, compliance with legislation is an essential link in this development. This research can, therefore, contribute to the acceleration of solving the problems as mentioned in the problem description, which can potentially have major social consequences.

1.6 Reading guide

In the second chapter, the current building regulation trajectory and the deviating trajectory when legislation lacks specific standards. This will provide an answer to sub-question 1. The following chapter has devoted the characteristics of a new innovation become clear and where 3DCP is now in the process will be described. Sub-question 2 will be therefore answered in this chapter. In chapter 4 a summary of all the current challenges with 3DCP will be tackled in order to get an idea of what still needs to be focused on and where 3DCP deviates from conventional concrete. Sub-question 3 will partly be answered in this chapter. Chapter 5 will perform a stakeholder analysis and will, therefore, answer sub-question 4. Finally, chapter 6 will present the roadmap for 3DCP in seven phases. The first two phases will be delved deeply, then phase 3 and phase 4 will be implemented in order to give an idea of the regulation of 3DCP further ahead. The report ends with the conclusion and discussion.

2 BUILDING REGULATION TRAJECTORY

To give advice about a possible roadmap for 3DCP, it is important to understand how constructive safety is tested in a regular process. Every public structure that will be built in the Netherlands will have to go through a regulatory process in order to get permission to build. Various parties will be involved during this regulatory process with their own functions. The role and function distribution during a tendering process can vary per tender. However, testing structural safety is, of course, a standard part of the construction process. In addition, it is being investigated how such a regulation process works with new innovations in which existing legislation falls short. Much has been described with regard to standards and regulations to guarantee safety. However, there is no collection that prescribes what is best when only separate safety islands in the regulatory ocean. That is why in Chapter 2 a collection of scenarios has been made about how to act (for municipality and market) in different situations. This collection is crucial to understand how a future roadmap can be shaped. Literature and interviews are input for this chapter.

2.1 Regulation and standards

The construction industry has a sort of love-hate relationship with standards according to the interview with Prof. ir. Wijte (Wijte, 2019). On the one hand, they serve as an agreement and can be used as principles to design and construct civil structures and buildings. On the other hand, standards and associated regulation can inhibit innovation. Many times, it is the industry itself that has to initiate such new standards in order to make new innovations scalable. But what are standards in the first place? Standards are a tool as a result of a broad-based consensus between several different parties. for example, standards can play an important role in the agreement between client and contractor. It is important to bear in mind that standards are the mean, where safety is the higher goal according to Wijte. Standards are almost never perfect. Since a standard is nothing more than an agreement, there is no right or wrong. Therefore, one standard is also more praised by one party than the other. A standard can, for example, has context and illustrations to make it easier to understand the idea and can contribute to the ease of use according to Wijte. What people not always realize is that standards are largely a private matter. There are subsidy flows for the most important widely supported standards such as the Eurocode, but for the rest, standards are financed by the market itself. Because standards are developed mostly by the industry itself. This also easily exposes the drives of organizations when they are committed to standardizing new technologies or products. Standards only have status if they are prescribed by European regulations or national legislation. It is therefore not mandatory to use standards if you do not need permission from the government. In principle, a standard document can be written by anyone, but if the reputation of the relevant organization or person is unknown or moderate and less is validated, the standard document will in all probability never be appreciated. Despite the internationalization of standards, technical regulations can vary considerably between countries. This is often the result of traditions from the past: "what are people used to?" according to Wijte.

2.2 Regular building trajectory

Basically, every regular construction process starts with a client with a specific demand for a new structure. The government is often the client for civil infrastructure projects, while the client is often a private party for industrial works and buildings. From a formal point of view, it is, therefore, the task of the client to apply for an environmental permit from the relevant municipality. Depending on the tender, the client comes with a set of requirements and wishes. It is then up to the market to tender this project, often involving a group of contractors in the form of a consortium that together has all the required expertise. In a practical sense, the client delegates structural safety assurance to the constructor. It is therefore often the task of the constructor who takes care of the technical implementation and delivers this to the municipality. It is then the role of the municipality to review the structural choices and argumentation on a number of assessment criteria, including the Building Decree (Bouwbesluit) structural safety. When the construction meets all the requirements, the permit is granted to the consortium can start building (see table 2.1).

Table 2.1: standard regulation trajectory phases

Phase	1	2	3	4
Actor	Client	Contractor	approver	Contractor
Function	set requirements and wishes	Design the construction	checks the design	manufactures the design
carried out by	government & private	Private company	Municipality	Private company

Structural safety assurance by the Eurocode

The client must be able to prove that what he wants to build meets the requirements of structural safety. These assessment criteria are written down in the Building Decree. This Building Decree refers to the European standards and guidelines for structural safety: the Eurocode. More specific, reference is made to the Eurocode 0 (NEN-EN-1990) which forms the basis of the structural design. The Eurocode then refers to the Eurocode 2 (NEN-EN-1992): Design of concrete structures. The Eurocode 2 delegates concrete standards such as material technology in EN 206. The 206 consists of standards in the field of Concrete - specifications, performance, production, and conformity. These collections of standards for concrete structure standards and the relations can be found in Figure 2.1.

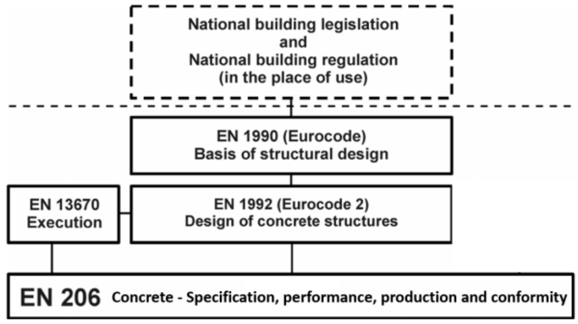

Figure 2.1: Relations between concrete Eurocodes (NEN, November 2016)

Responsibility

The client, which is the owner, is at all times responsible for the quality of the structure. So, it is not the government that bears the responsibility when it issues a permit, the government has only a testing role. Although the constructor calculates a design that is constructively safe according to him, he is not responsible if the construction fails. In addition, the contractor is only employed and does not bear the ultimate responsibility.

It is, therefore, the task of the client that all parties involved work according to the agreements. Practice shows that when a structure collapses, even though a permit has been granted, the fault often lies within the execution (Nijsse, 2018). It is often the case with incidents that the value that the constructor uses did not match the actual value. In principle, the calculation of the structural engineer is therefore meaningless if the wrong assumptions are made according to the interview with Wijte.

2.3 When The Eurocode falls short

The Eurocode covers a lot of the construction safety assurance. However, sometimes the Eurocodes 1 to 9 fall short. In this case, other standards that have less status than the Eurocode but can serve the building regulation trajectory. To use these documents, the so-called Equivalence principle (gelijkwaardigheid) is used within the building decree (Laagland, 2019). A condition is that the chosen solution offers at least the same level of safety, health protection, usability, energy efficiency and protection of the environment as intended with the applicable regulations (Ministerie van Binnenlandse Zaken Koninkrijksrelaties, 2012). This offers, for example, more room for applying innovative solutions. What kind of documents can serve as a solution is explained later.

2.4 When no standard exists at all

Currently, zero standards for 3DCP exists, also no technical recommendations that have a certain status exist yet. nevertheless, the first projects are now being constructed and open to the public. In order to ensure safety and gain permission from the municipality to build, intensive collaboration is required. Since the safety assurance is mostly based upon tests and (partly) newly developed test methods. It is, therefore, the role of the municipality whether sufficient safety has been proved. The key for the municipality is then to realize whether they have the competence to grant the permit according to the interview with Prof. ir. Salet (Salet T. , Ensuring safety when no standards exist, 2019) see Figure 2.2.

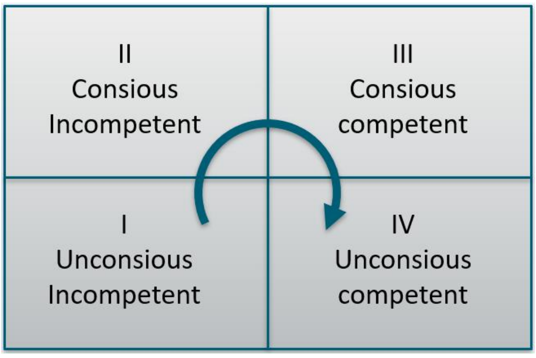

Figure 2.2: conscious/competent matrix (Broadwell, 1969)

A short description of each category will be given presented (Broadwell, 1969):
I Unconscious Incompetent: You don't know you can't do something. For example, the municipality sees a concrete structure being printed for the first time. In this phase, it is hard to estimate what the discrepancy is between the 3DCP technology and the Eurocode legislation.
II Conscious Incompetent: Now you know that you are unable to perform a specific function. You want to learn this, and you also know that it does not happen automatically, but that you need training for it, for example. This is happening to the municipality when a 3DCP project permission is requested. To provide the competence you have to arrange a substitute who can provide the skill for the time being.
III Conscious competent: You learn the competence by doing. At a certain moment, you are sufficiently competent and no substitute is needed since you are familiar with the phenomena. In the case of 3DCP this means that the municipality has the knowledge and no additional knowledge party is needed.
IV Unconscious competent: You have mastered the skill. Giving 3DCP projects permission to build feels like second nature and has become a routine task.
The problem for the municipality is that every municipality has must make this development for itself since every municipality is different. small municipalities are often in category I, where larger ones are often more in category II and outsource the required knowledge from third parties. This can be for example a comparable contractor or knowledge institution that has similar competence required (Salet T. , Ensuring safety when no standards exist, 2019). They key for the municipality is to act to their competitive level.

2.5 Conclusion

Permission to build in the Netherlands is done by the municipality. This means that this is handled locally. Building safety is guaranteed in the Building Decree, which then refers to the Eurocode regarding standards. If the Eurocode falls short, other documents can be used on the basis of equivalence in the building decree. The status of these other documents differ and must be properly substantiated in order to be accepted by the municipality. If no regulations are written, it is important that the licensing authority knows what the competence is about the subject to be able to grant a license. If the municipality is insufficiently competent to grant a permit, it is recommended to involve an independent knowledge organization in the permission.

3 DEVELOPMENT OF NEW INNOVATIONS

The risk with new innovations is that new inventions becomes a hype and eventually ends in a silent death because, after the hype, people tend to return to their conventional methods. Where people are attracted by the phenomena of concrete printing and the market is willing to pay for a bridge because it is printed. When more and more concrete structures are being printed, people start getting used to the idea and printing will get less attractive for clients just by choosing it because of the novelty of the product. Since the method is nowadays still far from mature and often more expensive due to intensive extra required tests. A parallel pattern can be found in the automotive industry. When an anomaly occurs in the form of electric cars. At first, a broad audience gets enthusiastic and a small group of early adopters wants to drive it even though there are still many disadvantages. to prove this disruption, in the long run, it has to be rationally the better choice and has to offer the best value most of the time. Two different perspectives have been chosen for this research: development of expactations with the wider public and the technological readyness of an innovation. Next, interviews are used to validate which phase 3DCP is currently in. In this way, it is possible to make a good estimate of whether it is time for standards or another regulatory instrument as part of a future roadmap.

3.1 Gartner Hypecycle

A much often used graphical representation of the maturity and adoption of technologies and applications, and how they are potentially relevant to solving real problems and exploiting opportunities is the Gartner Hypecycle (Fenn, 2007). This pattern also suits well for 3DCP where the Hypecycle plots the time against expectations and consist of roughly 2 phases (see Figure 3.1). These characteristics of these phases will be further explained.

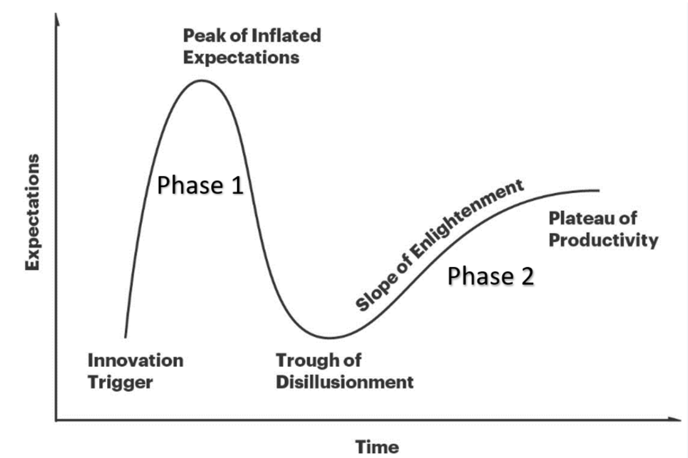

Figure 3.1: Gartner Hypecycle (Fenn, 2007)

Each Hype Cycle drills down into the five key stages of a technology's life cycle. a definition and link with 3DCP are explained per stage.

- ***Innovation trigger***: A potential technology breakthrough and potentials become clear. Early proof of concept stories and media interest trigger significant publicity. Often no usable product exist and commercial viability is unproven (Fenn, 2007). By installing a large gantry concrete printer at the University of Eindhoven, the field of 3DCP was ready to be discovered.

- ***The peak of inflated expectations***: Early publicity produces a number of success stories. Some companies take action; many waits and see (Fenn, 2007). The construction of words first 3D concrete printed bridge leads to a top hype level, where the world saw the first full application of the technology. Currently, 3DCP is clearly in this stage since the current projects receive major attention and the current projects can be seen as prototypes.

- ***Through of Disillusionment***: Interest wanes as experiments and implements fail to deliver. Producers of the technology struggle with evolving and the hype is decreasing (Fenn, 2007). Also for 3DCP, this implies that at a given moment the hype diminishes and the technology needs to be further developed.

- ***The slope of Enlightenment***: More instances of how the technology can benefit the enterprise start to crystallize and become more widely understood. Next generation products start to appear that start getting competing with the conventional method (Fenn, 2007). For 3DCP that means that tests should give more information on how to properly print concrete and create corresponding standards.

- ***Plateau of Productivity***: Mainstream adoption starts to take off. The technology's broad market applicability and reliance are clearly paying off. As for 3DCP, this holds that building companies have made from 3DCP structures a refined product and keeps the promises made in the beginning.
To go from hype to reality with 3DCP and make from the technology an alternative that can compete with traditional procurements and therefore offer a rational best value solution, a 3DCP internal transition is inevitable. This transition consists mainly of two parts: technology and legislation.
The technology of concrete printing has to be evolved in different areas in order to meet the best value solution. For example, the material, the construction behavior, and print parameters need to be more optimized and reliable. Another important development in the transition to reach phase 2 is to develop regulation for 3DCP in order to comply with legislation. Pre-standards could potentially resolve the now cumbersome permit process. Besides that, a side-effect will be a far less expensive method, when printing requires less testing (Laagland, 2019). The key aspects that are part of this transition can be found in Figure 3.2.

Phase 1		Phase 2
+ novelty		- commonplace
- No regulation	Transition →	+ pre-standards
- Proof of concept		+ optimised technique
- expensive		+ lower cost

Figure 3.2: key differences in phases

However, to make the transition, focus points need to be defined. Here the knowledge gap becomes clear since the concrete printing is still in its infancy and there is a lack of a proper holistic vision that provides handles to make a phase 2 tangible. To make a transition, the dot on the horizon has to be crystal clear, technological and legislatively (Wijte, 2019).

3.2 Technological readiness level

Technology readiness level (TRL) is a method for estimating the maturity of technologies during the acquisition phase of a program developed by NASA in the 1970s (Straub, November 2015). The use of TRL enables consistent, uniform discussions about technical maturity between different types of technology. The TRL of a technology is determined during a Technology Readiness Assessment that examines technology requirements, program concepts, and proven technological possibilities. The TRL is based on a scale of 1 to 9 and 9 is the most mature technology (see Figure 3.3).

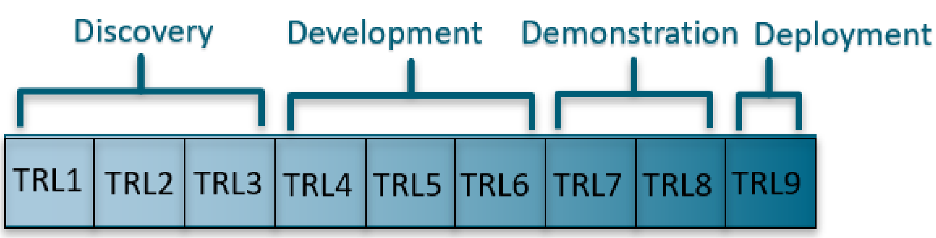

Figure 3.3: TRLs divided into four categories (Enspire Science, 2018)

The European Commission advised EU-funded research and innovation projects to adopt the scale in 2010. TRL in 2014 in the EU Horizon 2020 program. In 2013, the TRL scale was further canonized by the ISO 16290:2013 standard.

Table 3.1: definitions of all TRL (Straub, November 2015)

TRL	Discription
1	Basic principles observed
2	Technology concept formulated
3	Experimental proof of concept
4	Technology validated in lab
5	Technology validated in relevant environment
6	Technology demonstrated in relevant environment
7	System prototype demonstration in operational environment
8	System complete and qualified
9	Actual system proven in operational environment

Currently, 3DCP is making substantial leaps. By printing a full-scale usable bicycle bridge, they showed an experimental proof of concept and which relates to level 5. By printing more and more constructions in the environment, the technology went from the discovery phase to the development phase. One of the most important parts to go to the next TRL is creating more clarity in the field of durability: how does the material behave in the long run for example 50 years (Wijte, 2019). Both the Gartner Hypecycle and the TRLs can be combined to clarify the development of innovations like 3DCP because the increasing of TRLs pushes the innovation to the second phase (Wolfs R. , 2019) (see Figure 3.4).

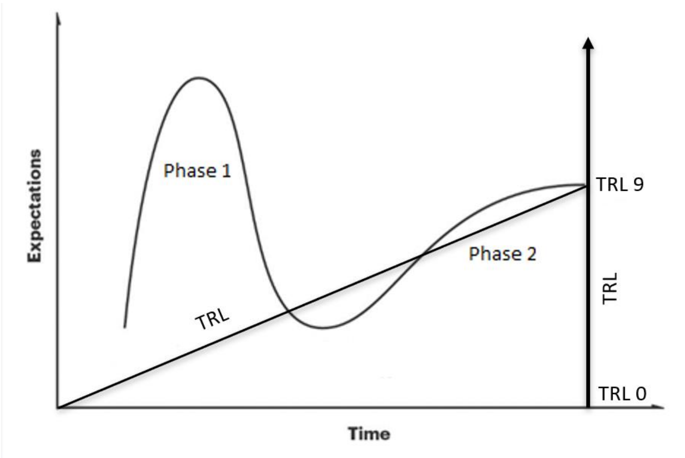

Figure 3.4: Gartner Hypecycle and TRL combined

Finally, it is important to define what best value situation means when 3DCP ends up in TRL 9. even the most optimistic 3DCP experts know that this innovation will not change the entire construction sector. Alternatives, such is prefab walls and masonry are simply not convenient to solve with printing. The key feature of printing is that it is really customizable. And since it is, almost, fully automated, industrial customization for scale fabrication will finally be possible and can, therefore, offer the best value solution in many cases (Bruurs, 2019).

3.3 The current state of 3DCP

In the Netherlands, with the first prototype bridge was opening at the end of 2017 in Gemert, the innovation trigger created great expectations about the potentials of 3DCP among the general public (NOS, Ocotober 2017) see Figure 3.5.

Figure 3.5: Opening of the first 3DCP bridge (NOS, Ocotober 2017)

At the end of 2019, a second more impressive printed bridge in Nijmegen (Cobouw, March 2019), a printed house in Eindhoven (CleanTech regio, October 2018)and a concrete printed meeting room in Teuge (CleanTech region, October 2018) will be finished. These three new structures, realized in the same period, are expected to create the absolute hype and really put 3DCP on the map (see Figure 3.5). To provide the Gartner Hypecycle in 2019 with more context, the Hype development for example of Crypto Currency (Labazova, Dehling, & Sunyaev, January 2019) and the electric car (Wilberforce, El-Hassan, Khatib, & Makky, Ocotober 2017) are also added in Figure 3.6.

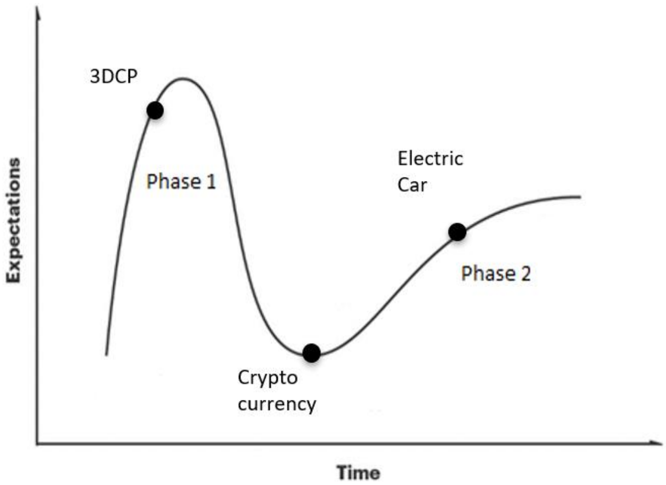

Figure 3.6: Gartner Hypecycle with some innovations

Because all these projects are already covered by prototypes and are seen more as proof of concept, the state of the current 3DCP can be seen at TRL 5-6 (Salet T. , the future of 3DCP regarding standards, 2019). The stadium of technology falls under development according to the category of Figure 3.3. When a robust system is further developed and work is done according to a fixed pattern, TRL 7 will be achieved (Laagland, 2019).

3.4 Conclusion

A new innovation can be mapped in various ways. One way is to involve the innovation on the Gartner Hypecyle, which shows that concrete printing is still ahead of the peak of inflated expectations. This means that the biggest hype is still to come and that the development is still in phase 1. Another way to map out a new innovation is through the technological readiness levels (TRL). According to this scale, 3DCP is currently in phase 5-6, which just falls into the category development. The goal of 3DCP is to end up in the plateau of productivity phase with regard to the Gartner Hypecycle and TRL 9 which means that 3DCP has become an actual system that is proven in the operational environment.

4 DEVIATING ASPECTS REVIEW

3DCP as part of Digital construction has gained attention and it has shown its potential in the past five years. Still, there are a vast amount of unresolved challenges which are up for future research. As mentioned earlier, to reach phase 2 in the Gartner Hypecycle as mentioned in chapter 3 where 3DCP can end up often in the best value position, a transition is needed, requiring more research. Research that has to be done on deviating aspects compared to normal construction techniques. This section lists a summary of all the deviating aspects that need to be investigated more: a discrepancy research. The purpose of a discrepancy investigation is to map all deviating points. By doing this review, a lot is mapped out and gives a good idea of the deviating nature of concrete printing compared to conventional concrete. Because this is also necessary to have knowledge of when standards are drawn up, this chapter has been included in the study. Along the way, new issues can always arise, so it cannot be said that when all the aforementioned challenges have been solved, quality and safety is ensured. Still, the following points are clearly to be investigated in this stage of developing. Finally, this research aimed to held consistency in the division: material design, structural design, and execution design. However, many challenges include two categories or an aspect that may indicate another deviation that is difficult to classify under one of these categories. Therefore, the following list has been drawn up with deviating characteristics that require further investigation. This chapter has been compiled on the basis of literature and interviews (see section 1.3). Because literature and the interviews are intertwined with each other for the knowledge input of this chapter, these forms of research are used interchangeably.

4.1 similarities 3DCP and conventional concrete

before all specific deviations are mentioned, it is good to consider the similarities between conventional concrete and printed concrete. It depends on which abstraction level you look at the differences/similarities. with a rough approach, you can say that there are many similarities: in both cases, the same cement, water, the corresponding hydration reaction is used. Also, the principle of mixing, pumping and placing concrete roughly corresponds to each other. Still, when zooming in on a specific component, it turns out that almost everything works differently with 3DCP, which will be described in the next section. Finally, a part that certainly remains the same is the pure mechanic rules, because they are independent of empiric assumptions (Bruurs, 2019).

4.2 3DCP specific discrepancy aspects

- Rheology:

Rheology (Greek for the study of flows) is the branch of physics that studies a number of flow properties of materials. A flow property that is characteristic of concrete printing is thixotropy (Greek for touch and motion). This pseudo-plastic property is characterized by a non-Newtonian liquid, whereby the viscosity decreases over time with constant shear stress. That is why mortar is always kept moving as long as it is not allowed to harden. After releasing the shear stress, the initial viscosity returns. For concrete, this means that the hardening process starts as soon as it stops moving. With the concrete printing, this phase transition takes place as soon as the material leaves the nozzle and is laid down. Because no formwork is used, the material will have to keep itself in shape after leaving the nozzle. This makes it desirable for the material to develop strength as quickly as possible. on the other hand, the material must also be workable. This means that it is miscible and that the material can still be pumped. Also, the rheological behavior of the material is often setting the limits of what is geometrically feasible to print.

These issues hamper 3DCP being fully known and usable, a critical milestone for commercial viability, of which rheological properties 3DCP materials are fundamentally important. It is, however, the hardened properties and conformity to design geometry that gives the manufacture component value. If these processes are to become common construction practice, it is essential to understand how to design structures to be manufactured with printed materials (Buswell & Dirrenberger, October 2018).

- Processing-Material-Performance:

Concrete material pumping is extensively used worldwide and is a mandatory processing step in digital concrete processes as it is responsible for the material supply, no matter the considered printing technology. Currently, there is no rigorous, scientifically based method to design a pumping circuit that maps the correlation between pressure and flow rate as a function of circuit dimensions and fresh concrete behavior. A relatively thin hose is very unusual in concrete manufacturing and a requirement for 3DCP and is therefore a deviating aspect. The flow typology within a pumping pipe is however complex and was shown in to differing from one of the typical viscous fluids such as water or oil (Kaplan, De Larrard, & Sedran, March 2005). Since 3DCP currently only

- Early age hydration:
As soon as the material is laid down, the material starts to develop strength. This first period after printing is called the dormant period (Berodier, Gibson, Burns, Roberts, & Cheung, January 2018). In the first hour after the material was placed, the cement barely reacted with the water. This reaction is also known as hydration. Yet, the material stays in place and there is little or no deformation. This is due to the so-called green strength. Green strength is a special concrete property that is created after mixing and compacting. This is caused by an adhesive reaction that arises between water molecules. The degree of green strength is highly dependent on the water/cement-factor and the fineness of the aggregates. It is, therefore, the green strength that makes formwork-free fabrication possible. As a result of the reaction, more and more cement will react with water. The desired concrete strength takes over here from the green strength. To prevent premature failure during printing, it is important that the material has sufficient (initial) strength at all times until it is fully hardened. This phenomenon depends on the one hand on material, since the material mix influences the rheology and the adhesion. On the other hand, the chosen dimensioning of the layers and the speed of stacking are more printer dependent. Since conventional concrete has a formwork and cannot collapse during the dormant period, this has never been a problem.
To understand the link between early age hydration products, their microstructure, and rheological behavior, more research is needed, for example (Wolfs & Salet, Early age mechanical behaviour of 3D printed concrete, April 2018). In Figure 4.1 is a numerical modelling experimental test executed that shows the developing of the critical points when the layers are printed, which is a research what an experiment is doing research into early age hydration and the speed of layer stacking.

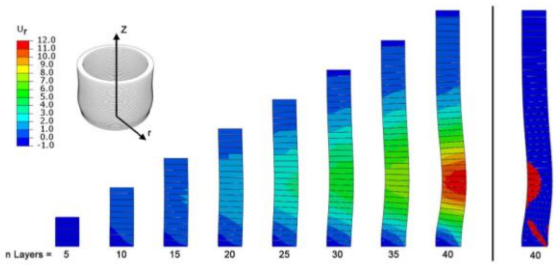

Figure 4.1: Early age mechanical behavior of 3D printed concrete
(Wolfs & Salet, Early age mechanical behaviour of 3D printed concrete, April 2018)

- Chemical admixtures:
As described early at the names and definitions. To give the material the desired behavior (e.g. a specific desirable rheological character), excipients in the form of admixtures often form this behavior. For example to accelerate the hydration rate of cement. Examples of admixtures are retarders, accelerators, and viscosity modifiers (Marchon, Kawashima, Bessaies-Bey, Mantellato, & Ng, October 2018). A more understanding of the impact of chemical admixtures on early hydrations, as well as interactions between numerous admixtures used in digital fabrication, would contribute to a more robust 3DCP process. Because other desired behavior is expected from the print material, other proportions or admixtures must therefore be developed for 3DCP.

- Computational modelling:
Modeling concrete properties during early hydration will prove essential for designing digital manufacturing processes in terms of optimum tool paths. Design algorithms in topological optimization are also the key for architects in creating more sustainable structures (Bonswetch, 2006). Finally, computational modeling on a molecular scale complements our understanding of early hydration and blending effects.

- Badge process vs. Continuous process
Because 3DCP is built in layers, it is therefore important that the bonding between the layers is not the limiting factor and that sufficient adhesion is guaranteed. To ensure good bonding, it is necessary to print continuously (Bruurs, 2019). When there is a gap in between the badges, the first printed badge will start curing, when supplementing with the next badge, the bonding between the two badges layers will be significantly lower, which can result in failure after all. Conventional concrete pouring is often applied in badges because the rheological requirements for poured concrete are much smoother, the concrete can also be supplied per cement truck, for

example. With 3DCP, the rheological requirements of the material are a lot stricter, which also has consequences for the printing process and it is always necessary to continuous.

- Reinforcement:

One of the major differences with 3DCP is the lack of conventional reinforcement bars in the material itself. because concrete itself has a very limited tensile stress, other alternatives will have to be thought of. Examples that take over the role of reinforcement are for example prestressing structures that are used for the bridge in Gemert and Nijmegen.

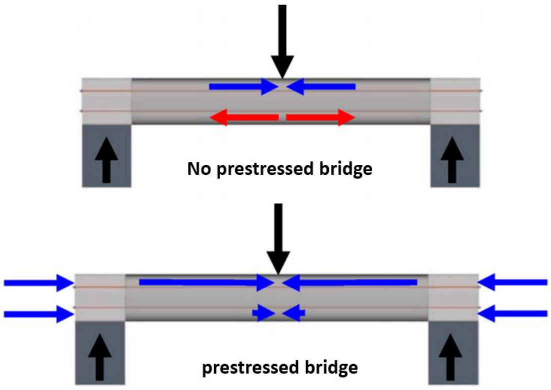

Figure 4.2: Difference in force distribution with and without prestressing
(Salet, Ahmed, Bos, & Laagland, 2018, May)

Another promising technique is printing steel fibers with concrete. Consistent quality with steel fibers in printed concrete is unfortunately difficult to manufacture, due to the requirements of the division and the direction of the fibers in the concrete (P. Pfändler, August 2018).
Also, an option is a concrete mixture design that can also be thought of that can handle some tensile strength on its own, so no additional material is needed to compensate the tensile strength. The disadvantage of using concrete and another component that can absorb tensile strength is that the material will not warn when it will fail, what reinforced concrete does.

- Test methods:

In order to perform tests, it is important to map the other parameters that may influence the result and fix them during testing a specific parameter. This is key in order to produce valuable results. The team at the TU Eindhoven (Wolfs & Salet, Hardened properties of 3D printed concrete: The influence of process parameters on interlayer adhesion, May 2019), for example, tries to map the parameters and the associated values that have to do with collapsing of a 3DCP structure in the early age hydration phase. New test methods that describe, how to print and with what for material, have been set up for this. The idea is that with this developed test method, other organizations can also perform the same tests according to the written method. By creating testing methods, you support reproducibility which is key in scientific research and forms the basis of developing standards.
Another important aspect that requires test methods is the interface strength with concrete printing (also known as bonding between the layers). A number of parameters are expected to relate to the quality of the bonding. Parameters that are yet known are interval time, the print head spread, the print nozzle height, and surface moisture content (see Figure 4.3). These parameters are all individually mapped (keeping the other parameters constant). These are some fresh concrete executing test examples.

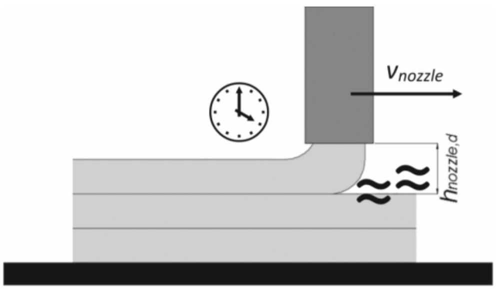

Figure 4.3: different parameters are related to the bonding between the layers (Le, et al., January 2012)

also due to the orthotropic nature of printing, additional tests must also be performed with regard to flexural strength see Figure 4.4. This is an example of a hardened concrete material test example.

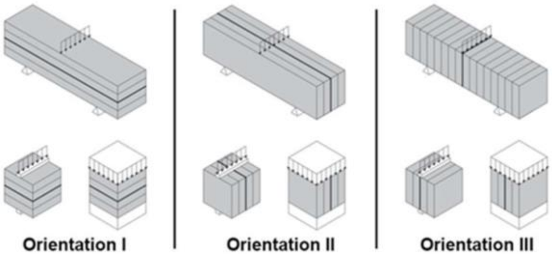

Figure 4.4: example of a test method for 3DCP flexural tests in multiple directions
(Wolfs & Salet, Hardened properties of 3D printed concrete: The influence of process parameters on interlayer adhesion, May 2019)

4.3 Other essential discrepancy aspects

In addition to a number of specific deviating points that need to be investigated, there are also a number of other issues that require a different approach with 3DCP or other large disruptive innovations in the building environment. These following points are more fundamental and holistic in nature and also expose some paradigms in construction.

- definition:

To be able to classify a material like concrete, the mixture must consist of cement, water and coarse aggregates. The material used for printing at the University of Eindhoven for example uses Portland cement (CEM I 52.5 R) as a basis (Wolfs R. , 2019). In addition, water has of course been added to allow the cement to react and bind. Use is also made of a silicon-containing aggregate with a maximum particle size of 1 mm (Blaakmeer, 2019). Finally, certain admixtures are added to achieve desired material properties, for instance, strength development. In that perspective, the composition differs greatly from the comparable conventional concrete mixes. According to the official definition (Berg, 1998), the material, which does not use aggregate with a diameter larger than 4 mm, may not bear the name concrete. Instead, the material falls under the mortar category and we are actually talking about a construction printed in mortar (see table 4.1). However, due to the widely used word concrete, people often talk about concrete printing and not of mortar printing. For the sake of uniformity, the research sticks to the definition of 3D concrete printing.

Table 4.1: names and definitions (Berg, 1998)

Mixture composition	Liquid	Hardened
Cement + Water	Cement paste	Cement stone
Cement + Water + Aggregate (<4 mm)	Specie mortar	Mortar
Cement + Water + Aggregate (>4 mm)	Concrete mortar	(Cement)concrete

- Sustainability:

Concrete mixes that are generally used with 3DCP contains higher cement percentage due to processing requirements and the lack of coarse aggregates. The production of cement, in general, produces a lot of CO_2 Emissions (Blaakmeer, 2019). As for the whole concrete sector, alternatives solutions have to be found in order to comply with sustainable development goals. An example of an additional side aspect could be researched on recycled concrete that can be transformed into the new 3DCP concrete mix to minimalize.

- Functionality:

Using precision material placement gives more opportunities to improve the functionality of constructing one segment. It is not inconceivable that in the future a printer will be able to print with different types of materials, for example, a 3D printer that can print heavy structural concrete, light filling concrete and insulation concrete in one print job (see Figure 4.5).

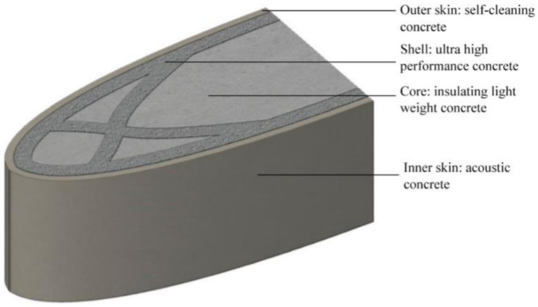

Figure 4.5: Concept of material customization by location
(Bos, Wolfs, Ahmed, & Salet, August 2016)

- *Creativity:*
The creativity of architects and structural designers had taken to the field, mainly because they found new and innovative applications of the developing technology. New applications drive technological development, making these processes more competitive in the long term with traditional construction. This gives people, especially architects, a whole new set of possibilities (Salet T. , the future of 3DCP regarding standards, 2019). since developments continue to develop rapidly, it will ultimately be possible to design any shape, which brings a lot of creative possibilities.

- *Interdisciplinary:*
What is apparent is how each of these research phases - material design, structural design, and executive design - have brought together somewhat disparate research areas into a single field. These research areas include material specialists, structural engineers who until know have experienced a "phase separation". However, the eclectic group includes also mechatronics specialists, who are able to engage with challenges of their own in digital fabrication (Buchli, et al., October 2018). Also, one of the most important roles: the architect, whose creativity and innovative designs are pushing the field forward by leaps and bounds. This indicates the interdisciplinary nature of this subject. Those disciplines form the core of 3DCP development. Yet, a greater potential may lie in bringing in even more disciplines such as computer science and big data analysis and machine learning according to van Damme (Damme, October 2018).

4.4 Conclusion

The research done in this chapter makes it possible to answer the question: At what points does 3D concrete printing differ from regular concrete? The most important findings in this chapter are that 3DCP differs in many different ways. They are however can be divided into direct 3DCP specific deviations and other deviations that might not have an influence on the regulation development, but it is important to know this because it can indirectly affect the speed of the transition to regulation. The findings are summarized in table 4.2 and 4.3.

Table 4.2: Discrepancy of technical aspects of conventional concrete and printed concrete

Technical Aspects	Conventional Concrete	Printed Concrete
Rheology	Concrete mixture design requirements are less specific	Concrete mixture design requirements are very specific
Processing-Material-Performance	Pumping circuit design requirements are less specific	Pumping circuit design requirements are very specific
Early age hydration	Early age hydration requires no specific requirements, becasuse the material is held together by the formwork	Early age hydration require very specific requirements, so that the material does not collapse immediately after printing
Chemical admixtures	Uses conventional admixture proportions	due to the new concrete mix design, the composition of the admixtures must be different from that of ordinary concrete
Computational moddelling	no computational input required	Requires a computational input to perform the construction
Badge vs. Continuous proces	Badge proces. An interval between badges is possible within the margins.	Continue. Printer may not stop in the meantime for the sake of product quality
Reinforcement	Standard Reinforcement applied in advance.	Printed steel wire, steel fibers, Pre-stressing
Test methods	Cube pressure tests is often sufficient	Orthotropic behavior and printer require new tests to define new framework

Table 4.3: Discrepancy of other aspects of conventional concrete and printed concrete

Other Aspects	Conventional Concrete	Printed Concrete
definitions	Often referred to as concrete, which is correct	commonly referred to as concrete which is incorrect. Technically it is a mortar
sustainability	Always had little to no environmental requirements	Also requires environmentally friendly solutions such as low-CO2 production
Functionality	One concrete segment consists of one material	One concrete segment will consist of different materials with different functionalities
Creativity	limited in design	Potential to design much more freely
Interdisciplinary	Ivolved relatively few professions	Involves a relatively large number of professions

5 STAKEHOLDER ANALYSIS

A stakeholder analysis is carried out in order to get a good view of how each stakeholder is involved in a regulatory process and what everyone's influences on the process are. The advantage of a stakeholder analysis is that more in-depth knowledge in particular organizations and phenomena can be obtained which can result in a more robust recommendation for the roadmap. A great opportunity to use as a case study for the stakeholder analysis during the research is a project in the Province of Noord-Holland. During the project, four small 3D concrete-printed bridges, meant for cyclists, will be printed in this project. This makes the project the first in the Netherlands where 3D concrete printing is used with scale, whereas previous projects always consisted of one single concrete printed structure. This makes the project a very suitable case since the scope of the research refers to providing 3DCP structures and scaling regulations. The first step with the stakeholder analysis is to map all the stakeholder with the corresponding definition to understand the specific stakeholder. After that, a power/interest assessment (Caputo, January 2013) is performed where each interest and power is analysed per stakeholder. Finally, to take stock, a power/interest matrix is filled in. The findings in this chapter were validated during interviews (see figure 1.1)

5.1 Stakeholder mapping

The case study of the 3DCP print project in the Province of Noord-Holland consists of the following relevant stakeholders (in alphabetic order):

- Academic Institute
- Architects
- Citizens
- Client
- Construction company
- Engineering company
- Licensing authority
- Material Supplier
- User

5.2 Power/interest assessment

Every relevant stakeholder is being assessed by first link the role to the specific organization, then the amount of interest and power is determined followed by an argumentation.

Academic Institute
Party: *University of Eindhoven*
Interest: relatively high
Power: relatively low
A University, especially the TU Eindhoven, is involved in the project since this project also contributes to the TRL of 3DCP. The University of Eindhoven can provide their existing knowledge to ensure safety on the newly printed bridge. Furthermore, the University of Eindhoven has the ability to print concrete and perform 3DCP tests.
The interest of this stakeholder is relatively high because the Academic institute supports more 3DCP constructions since this contributes to the overall knowledge of 3DCP.
The power of this stakeholder is low because this project is will be designed and constructed mainly by market companies who have now also gained the necessary experience. The university therefore only has a consulting role in this project.

Architect
Party: *Witteveen+Bos*
Interest: high
Power: relatively low
An Architect has a high interest in 3DCP since this new building technique opens doors to new shape possibilities, which is from an aesthetically perspective, important for the architect. Because the shape possibilities are still limited to concrete printing, the architect on this project has to bear in mind what the constraints are with printing.
The interest of this stakeholder is high because an architect is served by designing constructions that can shape in various contours.

The power of this stakeholder is relatively low because the architect is still limited in designing the bridge, due to for example the prestressed cables inside the construction and the limited cantilevering during printing.

Residential
Party: *Citizens*
Interest: relatively High
Power: relatively low
The people in the neighborhood are involved in the project since the bridge can change the environment by becoming a new landmark in the area, which can result in protest from the local residents.
The interest of this stakeholder is high because the locals do not want their sight lines to be obstructed by the bridge and becoming an undesirable landmark.
The power of this stakeholder is relatively low because the bridge can deviate from the design if there is a large-scale protest from the local environment, which is unlikely to happen.

Client
Party**:** *Provence of Noord-Holland*
Interest: High
Power: High
An incentive to be part of the project:
'Circular economy' and 'smart industry' are of paramount importance for the Province of Noord-Holland. These goals serve as an incentive to work with 3D concrete printing since 3DCP fits perfectly in the vision as explained in the introduction.
The interest of this stakeholder is high because the Provence wants to stimulate sustainability in the building environment and wants, therefore, to work with innovative methods such as 3DCP.
The power of this stakeholder is high because it is the client that draws up a plan of requirements where other parties have to comply with

Construction company
Party: *BAM*
Interest: relatively high
Power: relatively low
An incentive to be part of the project:
Concrete Printing is part of the research and development department for BAM and the company is one of the leading construction companies who invests in this new technology since BAM sees the potential of 3DCP and wants to be part of the transition.
The interest of this stakeholder is relatively high because BAM as a construction company wants to print more with concrete to get more familiar in the field and bring the maturity of their execution to a more robust level.
The power of this stakeholder is relatively low because BAM has to serve the wishes and demands of the client that pays and has an idea of the project. However, BAM is one of the leading companies to work with 3DCP and is therefore in a luxurious position to make certain decisions in the process for themselves.

Engineering company
Party: *Witteveen+Bos*
Interest: relatively high
Power: relatively high
3DCP is a very important topic for Witteveen+Bos since 3DCP is contributing to the sustainable development goals and this engineering company is very competent in the structural calculation of special constructions.
The interest of this stakeholder is relatively high because 3DCP is one of the priorities in the innovation portfolio. By doing more print projects, the company will gain more experience and contribute to innovation and TRLs.
The power of this stakeholder is relatively high because Witteveen+Bos makes the structural calculations and has a close relationship with printing facilities to tackle execution challenges that may influence the structural design.

licensing authority
Party: *Building Inspection Department of municipalities Alkmaar and Beemster*
Interest: low
Power: high
The licensing authority is responsible for giving permission to the public structures. this is arranged at the municipality level. Since the project covers two municipalities, it, therefore, has to deal with two licensing authorities.

The interest of this stakeholder is low because it is not the core business to stimulate new innovations, but instead to guarantee safety.
The power of this stakeholder is high because the licensing authority can stop the project if they are not enough convinced that the project is safe and meets all the standard requirements.

Material Supplier
Party: *Saint-Gobain Weber Beamix*
Interest: relatively high
Power: relatively low
3DCP has high importance by some material suppliers, as they see the transition towards digital construction, for example, 3DCP which requires a different concrete mixture design.
The interest of this stakeholder is relatively high because Saint-Gobain Weber Beamix recognizes the need for innovative concrete material, it is therefore very interesting for the company to provide the material for this new concrete printed bridge and can create a new market.
The power of this stakeholder is relatively low because Saint-Gobain Weber Beamix has to serve the wishes and demands of the client that pays and has an idea of the project. However, the material supplier is one of the leading companies to work 3DCP and is therefore in a luxurious position to make certain decisions in the process for themselves.

Users
Party**:** *Cyclist*
Interest: Low
Power: Low
The incentive to be part of the project:
The interest of this stakeholder is low because the cyclist has an interest in a bridge. However, for the function of a bridge, a conventional bridge can serve the demand of the cyclist as well. in the context of utilitarian bicycle traffic, it may be assumed that these have the purpose of going from A to B and do not benefit from a specific printed bridge (Bruurs, 2019).
The power of this stakeholder is low because the cyclist has little to no influence on the design.

Bringing all the results together in a summary gives the following power/interest grid results (see Figure 5.1). These results were validated during several interviews (Bruurs, 2019) (Laagland, 2019).

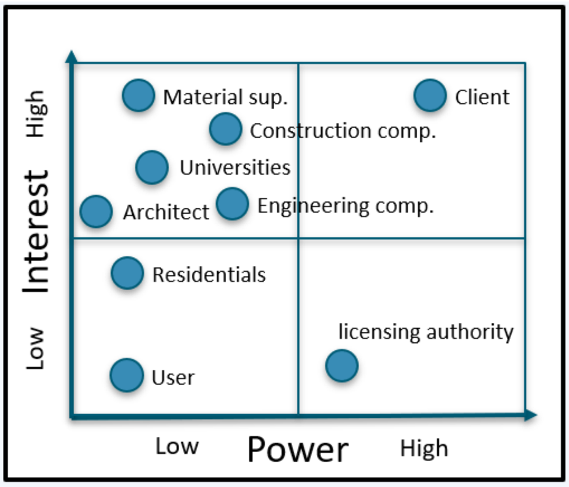

Figure 5.1: Stakeholder analysis 3DCP

The results of the stakeholder analysis are presented in appendix B in the form of an action plan where all relevant stakeholder is mentioned and advised what kind of action is expected from every party in order to continue the development of setting standards.

5.3 Conclusion

The research done in this chapter makes it possible to answer the question: Which stakeholders have importance in 3D concrete printing, and who can take which steps? The stakeholders are placed in a power interest grid and this analysis serves as input for the short-term roadmap implementation which can be found later in Chapter 6 under the heading action plan.

6 ROADMAP FOR 3DCP REGULATION

Since every construction consists of different phases regarding different disciplines, there are standards for each category. This section will elaborate on how the building environment deals with safety and quality assurance and how a new building technique can start with setting standards. Based on the previous chapters, the roadmap and the content of the roadmap have been established. Chapter 2 Building regulation trajectory contributed to the roadmap phases. Chapter 3 Development of new innovations made clear where 3DCP is and where things can go. Chapter 4 Deviating aspects review provided insight into current challenges, which provided insight into the implementation of the first phases of the roadmap. Chapter 5 stakeholder analysis results in an action plan. This is described in the Implementation in the near future (phase 1 & 2). This roadmap for 3DCP regulation has been developed out of various interviews (Wolfs R. , 2019) (Dijk, 2019) (Blaakmeer, 2019) and literature (Salet T. , Protocol printed bridge, October 2018).

6.1 Long-term roadmap

The following roadmap was validated (see appendix A) with interviews (Wijte, 2019) (Salet T. , the future of 3DCP regarding standards, 2019) (Bruurs, 2019). The deliberate decision has been made not to link a timeline to this because the speed with which these phases are completed is highly dependent on technical developments, willingness to cooperate and share knowledge, and the financial resources. In the end the roadmap was framed in 6 different phases. These are listed below in chronological order and briefly explained.

Phase 1 - Test protocol

For the first 3DCP projects that are used publicly, safety is guaranteed by being related to the Eurocode: Design By Testing. This prescribes which tests must be carried out to ensure safety. For 3DCP this now consists of more extensive material testing, a structural test by performing a Mock-up test, a test load on the end product and durability testing. These tests are written down in a protocol that is specifically written for the project of the first phase. The printed bridge in Gemert is built with this protocol.

Phase 2 - Improved Test protocol

For follow-up projects with the same 3DCP partners, Design By Testing will still be applied with the same protocol. However, when the same material is used, the mapped material information can be reused, resulting in fewer material tests. If the to build structure deviates strongly from previous designs, it is recommended to make use of a Mock-up test in this phase. If the engineer has specific questions about a certain part of the structure, it is possible to consider testing this component only for structural safety. A test load is not mandatory but is strongly recommended to convince all parties of the actual used structure that safety is ensured. It is also recommended to continue monitoring the durable behavior of the structure over time.

Phase 3 - 3DCP report with technical recommendations

Several parties continue to provide and enhance their own safety protocols to obtain a permit. Because often with a 3DCP project, a municipality comes into contact with 3DCP for the first time, the building consortium must again explain its own safety protocol and convince it that it is sufficiently safe. Different parties who are walking around with the same problem will have to visit each other and make a report that maps out how security is assured with 3DCP. By having several parties reach a consensus, the quality and status of such a document will increase. The status of this document is a report (Dijk, 2019), which means that this is just an advisory document.

Phase 4 - Standard Supported open Pre-standard

When several parties have sufficient knowledge to support their consensus, this work can be submitted to a standardization institute with rich experience in setting standards. If all parties support the written standards with sufficient confidence, the technical agreement will be published as technical recommendation and has the status of pre-standard. This means that the pre-standard has sufficient status to demonstrate safety in most municipalities due to this specific quality mark. Characteristic of this pre-standard is that it has been developed by different partners from different fields and different consortiums. In addition, no specific product brands are mentioned in the standard in order to not to exclude other companies. A similar process, for example, can be found with the high-rise covenant in the Netherlands. All relevant market parties involved in high-rise have come together to come to a qualitatively uniform document, in which they first had to guarantee their safety individually (like in previous phases).

Phase 5 - Eurocode consisting of the Dutch appendix
When much use is made of a pre-standard and it proves itself frequently in practice, a pre-standard can be included in the Dutch annex to the Eurocode. In terms of construction safety, this is the highest attainable in terms of standard status in the Netherlands.

Phase 6 - Eurocode
To include this knowledge in the full Eurocode it must also be accepted internationally, which will lead to a new discussion since each country has its own building safety culture (Wijte, 2019). The consequence for this may be that the standard is formulated in a very generic way and that it is given specific regional interpretation.

Implementation of the roadmap
We are currently still largely in phase one (Laagland, 2019) and this report is trying to put things clearly and contributes to the implementation of phase two (see figure xx). A recommendation is also made for phase 3 and phase 4 as these are important to take into account when developing phase 2. Phases 5 and 6 will not be discussed in more detail because they are too far to provide a sensible interpretation (see figure xx).

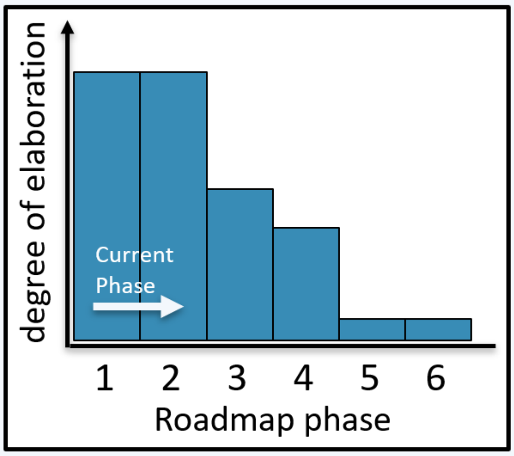

Figure xx: degree of elaboration per roadmap phase in the research

6.2 Implementation in the near future (phase 1 & 2)

Design By Testing
The first step in quality assurance with new building innovations can be found in the normative appendix D of Eurocode NEN-EN 1990-1-1 (NEN, December 2011). This appendix describes the so-called Design by Testing method that makes it possible to design structures with new materials or techniques that are not described in current normative legislation. Design by testing (also known as DBT) is often a good starting point when it comes to ensuring safety and from which new standards can arise (Salet T. , the future of 3DCP regarding standards, 2019). Design by testing offers the 'easiest way out' since everyone in the field is familiar with the code and building on the Eurocode gives reliable tools in an uncertain early phase. Other innovations that have evolved out of its infancy with DBT are for instance monolithic floor. Design by Testing stipulates that material properties must be determined on the basis of standardized tests. It is also necessary to perform tests to map structural parameters and determining the behavior of the actual construction. Design by testing makes distinguish between seven different testing categories (see table 6.1). To guarantee the quality, each test category must be sufficiently executed (see table 6.1). The table also connects every test description to the self-made testing category division. each test method falls. These test categories will be expanded on later. To give implementation with Design By Testing for 3DCP, a flowchart has been set up that maps all the testing categories that covers all test descriptions that the Eurocode prescribes.

Table 6.1: Testing categories with Design By testing (Normalisatie-instituut, 2011) order.

Category	Description (NEN, December 2011)	Testing category
a	Determine extreme resistance or usability properties	Structural Tests
b	Determining specific material properties	Material & Durabillity Tests
c	reducing uncertainties in parameters related to load models	Structural Tests
d	reducing uncertainties in parameters related to resistance models	Structural Tests
e	Tests to test the quality of the delivered product	Construction Tests
f	Tests during execution to get data for part of the execution	Construction Tests
g	Control tests to test the behavior of the actual structure	Construction Tests

3DCP DBT Flowchart protocol

To provide this quality assurance for 3DCP with handles, a protocol has been drawn up in the form of a flowchart (see Figure 6.1). This flowchart describes how you could apply Design by Testing to 3DCP projects to ensure full quality. This division is inspired by the previous and also the latest Dutch standards. The quality assurance for concrete is divided into concrete structural design, concrete execution, and concrete material. These guidelines are inspired by the previous and last nationally used standards. In table 6.2, the connection can be seen between formerly and current standards for every category.

Table 6.2: linking design categories to standards

Category	Standard
Material Design	EN-206
Structural Design	Eurocode 2
Excecution Design	EN-13670

These categories together with the previous existing protocol (Salet T. , Protocol printed bridge, October 2018), forms the basis of the new developed iterated flowchart protocol that ensures quality for 3DCP.

The protocol is arranged in such a manner that all design phases in the upper row consist of fixed questions. Each category can be supported with the help of experiments. These are also divided chronologically into four test categories that together form the bottom row. The implementation of the test categories can differ. To determine what sort of tests should be performed for each category will be furthermore explained.

It is possible to only perform parts of these tests for a project. In the first 3DCP projects, when an insufficient amount parameters have been mapped, all test phases will be addressed. who must perform which test is explained later. As more experience is gained, more will become known about the material and it is not necessary to perform some tests because the knowledge of previous tests is sufficient. When complete research has been done into the properties of the material with reliable results, these results can also serve for future projects, that uses the same material. In this way, it is possible to renounce Design by Testing slowly. Ultimately, technical recommendations will arise based on empirical research that results from the testing. These make it possible to print concrete in the future that does not require time and financial intensive tests. One of the most time and financial intensive test is the mock-up test. The mock-up test is carried out when there is so much uncertainty about the design that a second (scale) model is made. This is to test the structure with maximum load, and to validate whether the actual structure is strong enough. This flowchart is an interpretation based on in-depth expert interview validation (Laagland, 2019) (Salet T. , the future of 3DCP regarding standards, 2019). The order, however, may differ with each project as long as every category is sufficiently covered. It is, for example, conceivable that first the execution parameters are being covered and first then material testing and design.

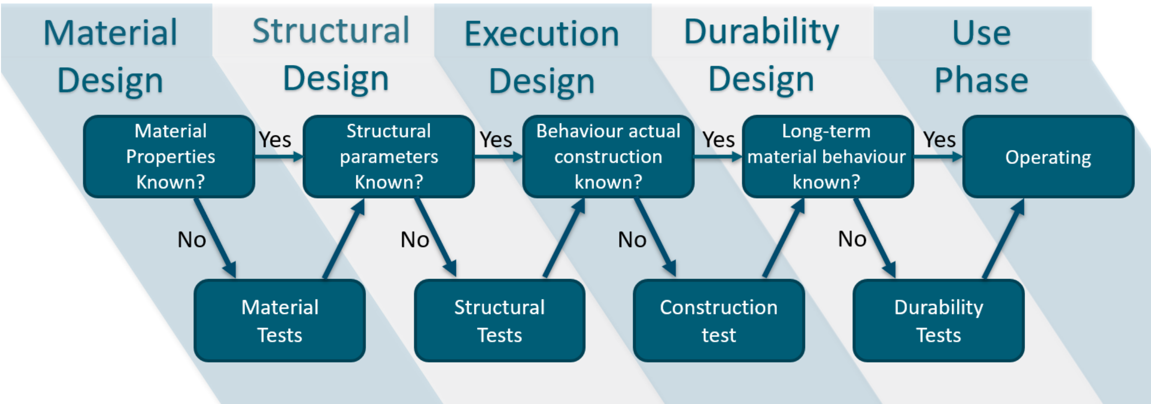

Figure 6.1: Design By testing flowchart protocol for 3DCP

The complexity of 3DCP categories division

The flowchart protocol in Figure 6.1 demonstrates a manner to cover all different categories with design by testing. A linear flow chart has been chosen in this research because it serves as a logical step-by-step heuristic plan: you where how to start and where to end. Also, in the Dutch construction culture, people are also used to this traditional order which therefore contributes to the ease of use (Wijte, 2019). Finally, one of the goals with designing the flowchart protocol for DBT and 3DCP was simplicity. This may end up a quite superficial but everyone can understand it. however, the fundamental problem with 3DCP is that all these different design phases are deeply interlinked. An object must fulfil a function, which requires a particular shape, into which material must be processed. Choices that have to make with every aspect can have a major influence on another aspect. For example, when using pretension tendons for structural safety, the freedom of the shape of the object is very reduced in possibilities since steel wires are prestressed inside the object.

Implementation design by testing

The testing categories of the flowchart are divided in a traditional chronological order (i.e. a fixed start and end point) and every category has it's corresponding tests in order to support the design phase. Each design phase has its own flowchart on itself that helps to determine what kind of tests should be performed in order to ensure safety. what and how much should be tested depends on how much is known. If little is known, more testing is required. If more is now known about a certain phenomenon (e.g. due to experiences with previous comparable tests), it is possible to opt to perform fewer tests. The test implementation according to the 3DCP DBT flowchart is as follow:

- ***Material Design***

Certainly, when this material has a supporting function, things such as compressive strength, shrinkage and creep must be clear in order to be able to design. To what specific level tests should be performed depends on what is known about the material and how it behaves when it is printed. When the material is totally unknown, it is necessary to perform intensive tests in different directions (also known as orthotopic behavior) according to interview with R. Wolfs PhD (Wolfs R. , 2019). When the right type of experiment has been chosen, it is important to have a sufficient sample size conform to the requirements of the Eurocode. See the flowchart in Figure 6.2 for the implementation of the material tests and how to come to the next design phase.

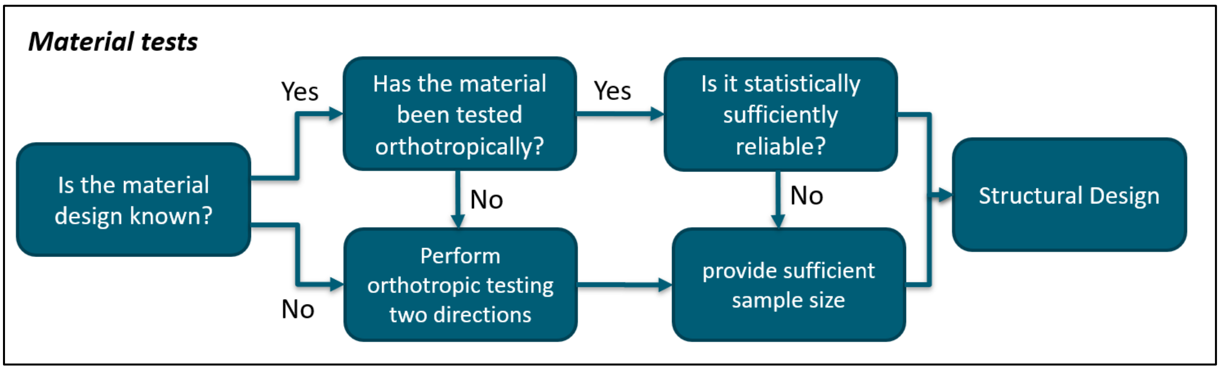

Figure 6.2: Material tests implementation

An example of testing of hardened concrete to determine printed concrete material behavior can be seen in Figure 6.3. This a typical example of a material that has been tested on orthotropy with a sufficient sample size. Whether the sample size is sufficient is described in annex D of Eurocode 0 (NEN, December 2011). When the material tests are properly performed in an scientifical manner with a sufficient sample size the next design phase can start, which is the structural design.

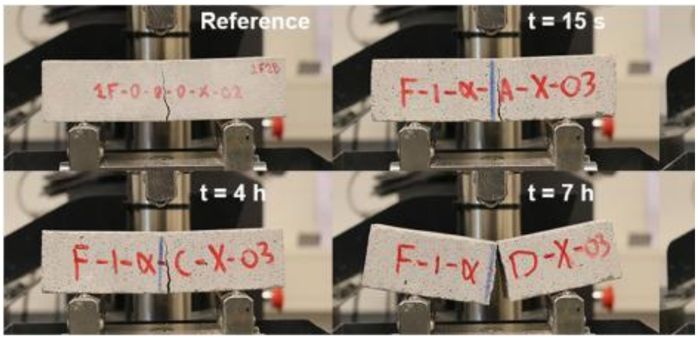

Figure 6.3: 3DCP Material flexural test (Wolfs & Salet, Hardened properties of 3D printed concrete: The influence of process parameters on interlayer adhesion, May 2019)

This test determines one single correlation to contribute to the whole material behavior, namely the adhesion between the layers at different time between the printing of the layers. It is, therefore, necessary to test with a sufficient sample size in order to be statistical reliable as prescribed by the Eurocode. In addition to flexural strength, which first has to be tested in several directions (see Figure 4.4), one can also consider material properties such as compressive strength, cross-contraction coefficient, shrinkage and creep. All of these properties must first be tested orthotopically. (Salet T. , Protocol printed bridge, October 2018)

- Structural Design

When the material properties have been mapped, a structural design can be prepared. It is important here to check whether the structural behavior of the construction is known, which assumptions can be made? In addition to the basic material properties, other phenomena may occur when the material is used in a certain manner so that the construction can still collapse. For the design of the 3DCP structure, it is very important to design with the print capabilities in mind. When little or nothing is known of a structure, a (scale) model (also known as Mock-Up) is being built to perform mock-up tests. When more tests are performed on a familiar structure and the structural engineer has only some specific questions, it is possible to perform specific additional component tests instead of an entire mock-up test. For example on the vertical bonding between layers. For these specific questions, it is also important to have statistical reliability when performing specific structural tests. See the flowchart in Figure 6.4 for the implementation of the construction tests.

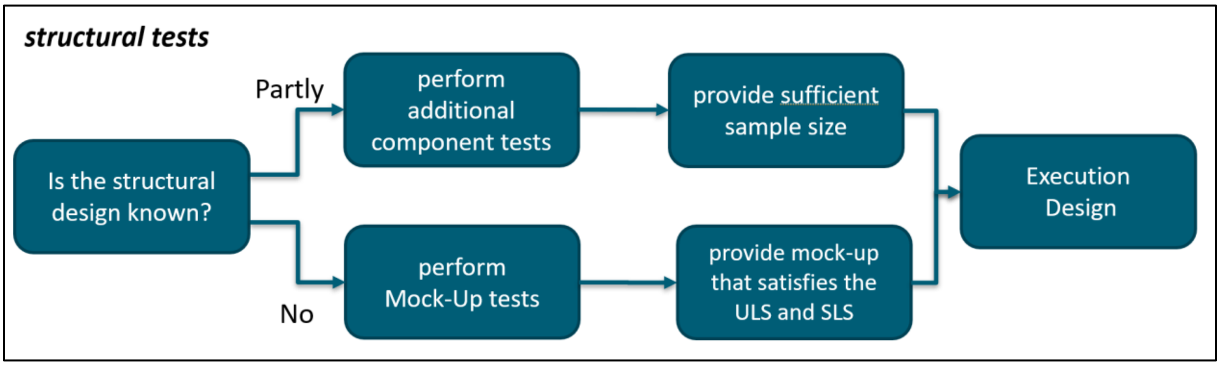

Figure 6.4: Structural tests implementation

An example of a mock-up test can be seen in figure 6.5. This mock-up test is to determine how the proposed construction behaves in the ULS and the SLS. These loads will never have to withstand the structure actually used, the construction test is for that.

Figure 6.5: Mock-up test setup to determine the SLS and ULS.

Such a mockup test is carried out when a high degree of uncertainty is on the structural behavior. Therefore, a duplicate structure is tested for maximum load. If the structure does not deform too much, the actual structure can be printed in the execution phase. As more becomes known about the structural behavior of printed concrete structures, specific additional tests that the structural engineer has can be looked at. Because this happens at component level, it is important that the results are reliable. For this it is important to provide a sufficient sample size (see Figure 6.4). For a new 3DCP project in Noord-Holland. For a new project in Noord-Holland an attempt is being made not to perform a mock-up test but an additional component test (see appendix B).

- ***Execution Design***

If the structural behavior of the design is sufficiently known and reliable, the actual construction can be printed. It can happen that the actual final construction still behaves differently than the printed test Mock-up. That is why it is necessary to carry out a construction test. These tests check whether the quality of the final product corresponds to the predetermined calculations. The construction test load on the bridge is not to test the ULS, because that could cause unnecessary damage to the final product. An example of a final construction test can be seen in Figure 6.7. When deflections are measured, it must be determined by experts whether it is safe to use the bridge or modifications must first be made, see the construction flowchart in figure 6.6.

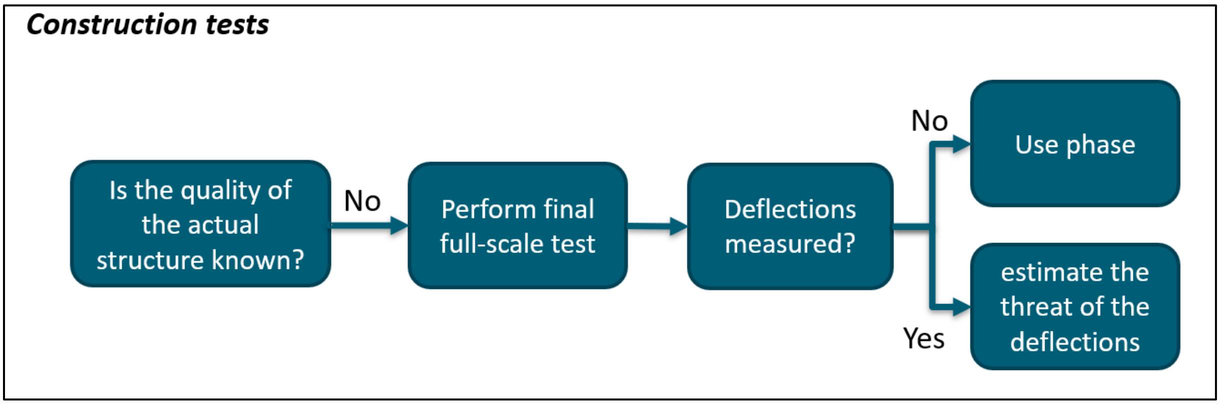

Figure 6.6: Construction tests implementation

the first printed bridge in Gemert (see figure 3.5 & 6.7) had a construction test on site to make the bridge work as expected and to be structurally safe. Tests like these are of course non-destructive and are used on a regular basis to verify the capacity of older and existing infrastructure. As shown in Figure 6.7, the bridge was loaded with 10 containers filled with 500 liters of water. Including their own weight, this resulted in a total load of 57 kN on the bridge. The holders were positioned such that 100% of the usability limit state bending moment was achieved. The resulting deflection was too small to measure.

Figure 6.7: Final construction test (Salet, Ahmed, Bos, & Laagland, 2018, May)

- ***Durability Design***
One of the most difficult parts to guarantee the quality is the durability aspect. Does the structure still have sufficient capacity in 50 years? Solutions for this have been found by, for example, making an inspection protocol that consists of key parameters which must be monitored more intensively. For example, tests that monitor the creep at critical points of the bridge. Because the 3DCP material is known for its high creep, the scenario can occur that the prestressing tendons are losing the tension because of the creep and the shrinkage of the structure (Laagland, 2019). The flowchart in Figure 6.8 provides an idea of what kind of durability tests should be performed.

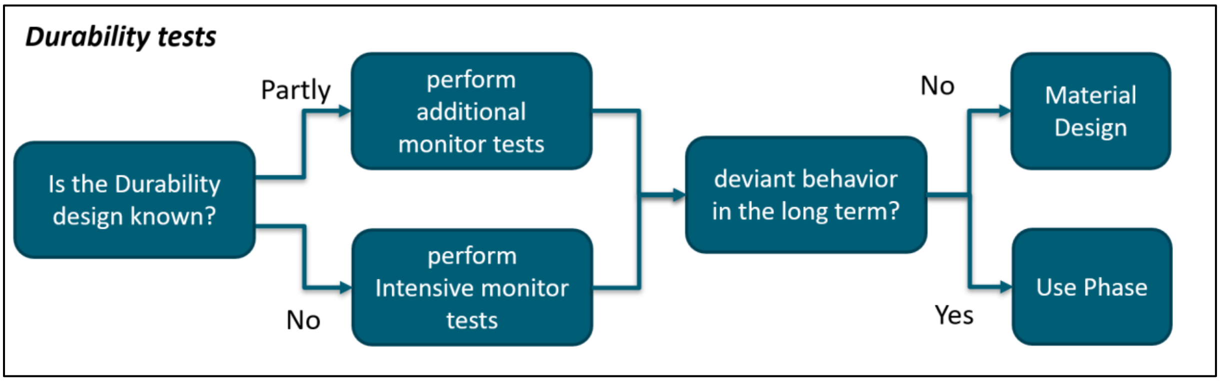

Figure 6.8: Durability tests implementation

To demonstrate the durability flowchart and associated test flowcharts, two different projects have been entered in Appendix B for the protocol with an implementation of the chosen steps in the flowchart.

- Use Phase
When everything is designed, executed and the final construction test is approved, the construction can proceed to the use phase. The structure will become asset management for the owner in the use phase (Bruurs, 2019). As mentioned earlier, one of the biggest questions when it comes to quality assurance is the durability of 3DCP structures. One concern, for example, is the shrink and creep behavior in the long run. Due to this uncertainty, intensive monitor tests are required in order to map the durability and ensure safety also for the coming decades. Because of the confidence in the design, it can be decided to go directly to the use phase and do intensive durability monitor tests at the same time, this is done, for example, at the bridge in Gemert (Wijte, 2019).

Action plan

based on the stakeholder analysis that is linked to the case study in Noord-Holland. The functions are kept generic and no specific parties choose the roadmap. this action plan focuses in particular on the implementation of the phases we are currently in (transition from 1 to 2). The action plan is not specifically recommended for the following phases because it is too far away. However, it can be assumed that the roles will not differ greatly from those described below.

- Academic Institute

The role of the academic institute it to perform experimental tests in order to do scientific research which forms the basis for the knowledge production of 3DCP. By doing tests it becomes more and more clear which parameters are of importance and which not.

- Architects

Because 3DCP is still in its infancy, the print possibilities are still quite limited. It is therefore important for the architect to design with the printing possibilities in mind. When the technology will evolve more over time, the design options will have fewer limitations. But in the current phase, architects must design with the printer in mind.

- Client

The client should realize that current 3DCP projects are still very far from mature and carry more risks than conventional proven building principles. Therefore, the client must be flexible and should be involved in the construction process for every phase.

- Construction company

Since the construction company is responsible for the execution task, they have to develop and optimize a robust printing technique that tackles all small issues, that currently still exists.

- Engineering company

From an engineering perspective, it is important to make the right structural assumptions when determining the structural behavior of the construction. The engineer can ask to perform specific tests in order to make the right assumptions.

- Licensing authority

The licensing authority has in the early phase an important role since bespoke conversations should be held. In this early 3DCP phase it is important that the licensing authority is aware of its incompetence and therefore should seek external advice from another knowledge institute to determine the safety of the whole process.

- Material Supplier

As for the engineering company, the material supplier has an important role in design the new concrete mixture which is key to provide a mature 3DCP concept. For the material supplier, it is therefore important that the material can reach certain requirements in order to

6.3 Implementation further ahead (phase 3)

When the protocol has sufficiently developed and proven, the decision can be made within the specific consortium to write down the knowledge of the empirical data that the tests have yielded and that have been scientifically performed. This so-called technical recommendation is the first form of a standard, but the status is still very limited as described in chapter 2. Phase 3 describes how the first form of a new standard can be written down and what should be considered.

Writing new standards

When you start drafting a new standard, it is important that the right distinctions are made. In the Netherlands, people are known for the separation of material technology, Design, and execution. This distinction is made because each part often appeals to a different party (Salet T. , the future of 3DCP regarding standards, 2019). It is customary for pre-standards that they prescribe something in all three areas when creating a certain innovation. In the context of uniformity and usability, it will, therefore, be advisable to make this separation in the technical recommendation for 3DCP. That is why it was also recommended in the previous phases to maintain this separation for 3DCP.

The abstraction level of a standard

As described earlier in chapter 2 standards have a love-hate relationship with the construction environment. On the one hand, they offer guidance in the realization of safe structures and are necessary to make good agreements. But on the other hand, they often stand in the way of innovation. This balance can be seen as the level of abstraction of a standard according to the interview with M. Bruurs (Bruurs, 2019) (see Figure 6.9). In the case of abstraction levels, a distinction can be made between generic and specific (Perrenet & Kaasenbrood, June 2006). Both will be discussed, the potential and will both be provided with contexts to illustrate future standard possibilities.

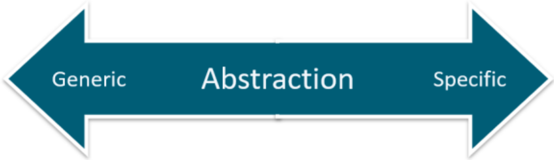

Figure 6.9: discrepancy in abstraction

Generic written standard
A generic standard only describes the essential broad outlines of the safety requirements that must be guaranteed. In the base, standards exist to make sure things are safe. In the most generic form, a standard may prescribe: "The concrete structure must be safe". The advantage is that this set-up gives a lot of degrees of freedom and innovation will by no means inhibit. In addition, the standard is now ready and the standard is so generic designed that all buildings comply with this standard. Unfortunately, this design has a significant disadvantage, mainly the lack of handles for concrete printing, which is also a characteristic of a standard. An example of a less generic standard for concrete printing could be as follows:
- Example of generic standard
Material Phase standards:

- Develop a material mix design to guarantee certain environmental classes.
- Develop own material tests in order to map material properties and prove uniform behavior.
- Develop own method to comply with prescribed material conformity.

Structural Phase standards:

- Determine calculation values of material properties
- Determine a structural model that corresponds with the real structure behavior

Execution Phase standards:

- Develop a printer that can duplicate the digital structure to a physical model
- Check whether the actual structure behaves like the proposed model

Specific written standard
A specific written standard is very clear and extensively written. This results in a standard that offers solutions for a limited amount of 3DCP projects. In the most specific form, it can be thought of a 'Gemert-standard', which is a standard that describes everything that you should do in order to build a replica of the bridge in Gemert (Bruurs, 2019). The advantage is that nothing is unknown, because every step has been done before and validated. The drawback thus, however, is that you only serve people that want to duplicate an already existing bridge and does not offer guidance to new deviating 3DCP projects, which really inhibits innovation as mentioned in the introduction. An example of a less specific standard for concrete printing could be as follows:
- Example of a specific standard
Material Phase standards:

- Prescribed material mix that guarantees certain environmental classes.
- Prescribed requirements for control methods of the material
- Prescribed performance requirements of the material
- Prescribed conformity criteria
- Prescribed production control

Structural Phase standards:

- Calculation value of material properties
- Orthotropic approach
- Compressive strength
- Tensile strength
- Creep and shrinkage
- Prestressing tendons

Execution Phase standards:

- *Executive management*

- *Printer specifications*
- *Nozzle specifications*
- *Supporting cantilevering*
- *Executing prestressing tendons*
- *Layer bonding requirements*
- *Measures in case of deviations*

A general overview of the discrepancy with a generic written standard versus a specific written standard can be found in Table 5.2.

Table 6.3: summary generic vs. specific standards

Generic	Specific
+ freedom for own implementation	- hard to vary in design
+ widely applicable	- niche market
- vague	+ distinct
- lot of custom implementation per project	+ less custom implementation per project

6.4 Implementation further ahead (phase 4)

As described earlier, standards in the form of technical recommendations derive a certain status. There are certain organizations that have become authoritative in developing codes, because of the quality of the documents that they have created in the past and that are widely appreciated. In the Netherlands, there are currently two independent organizations with a good reputation that publish technical recommendations. Quality is often guaranteed under their flag, which often leads to approval by the licensing authority for matters that are not included in the Eurocode. The organizations that have built up status over the years with their published works are the Dutch Standardization Institute (NEN) and CROW. Both have different characteristics, but they do not differ much in terms of status and quality of the documents. For 3DCP it is interesting to make use of such an organization to bring quality assurance to a certain status level with technical recommendations. This research does not make a recommendation as to which organization is preferable. This research has only an informative role in making of such an assessment.

NEN / Dutch Standardization Institute

The Dutch standardization institute (NEN) is the Dutch platform for all standard development and managing (NEN, sd). This institute develops various types of standard agreements such as standards, practical guidelines or technical agreements. The NEN is also responsible for the translation of the Eurocode The most accepted agreement is the Dutch standard (NEN standard). A characteristic of a NEN standard is that it represents a broad group of interested parties. The result of this is, therefore, a norm with broad support and significant status (Wijte, 2019). In addition, the NEN also has Dutch pre-standards (NVN). This is a provisional requirement-setting agreement with partly missing provisions. The intention is to publish the agreement as a Dutch standard (NEN standard) if further tests or adjustments have been made and a consensus has been reached. The more testing is carried out, the more uniform and complete the testing results will be, the sooner an NVN can become a NEN standard. The NEN also uses Dutch practical guidelines (NPR). These agreements are informative in nature and, just like the NEN standard, have a broad representation of interested parties. The result of an NPR is, for example, a description about constructive possibilities. Finally, the NEN offers a Dutch Technical Agreements (NTA) option. An NTA is a demanding agreement that is supported by at least two or more interested parties. An important difference between the other standards is that an NTA does not require an imminent consensus. An NTA is also characterized by a short development time. The result is an agreement that can be made relatively quickly compared to other documents. This brings added value when there is still a lack of regulations for a new rapid developing innovation. An example of an NTA is the high-rise building covenant that offers technical recommendations for high-rise buildings in the Netherlands where codes fall short. See table 6.4 for an overview of all the standard agreements that the NEN offers.

Table 6.4: forms of NEN agreements (NEN, sd)

Name	Status	develop time	Approach
NEN	High	3 years	Demanding
NVN	Avegare	< 3 years	Demanding
NPR	Average	1 year	Informative
NTA	mediocre	< 1 year	Demanding

Within these possibilities that the NEN offers, an NTA is the most appropriate option for 3DCP, since this agreement can get well on with new early stage innovations and a consensus is not required imminent.

CROW

In addition to the Dutch standardization institute, a Dutch independent knowledge platform CROW has set up CROW recommendations. A CROW recommendation is the best technical advice that can be given on a particular subject at that time (CROW, 2016). This stimulates innovations in regulation and prevents uncertainties and incorrect applications. The content of a CROW recommendation has the character of a standard, because of the wide acceptance, a CROW recommendation can be seen as pre-normative documents. The establishment of a recommendation is designed by a committee consisting of relevant market parties (Dijk, 2019). An important characteristic of a CROW recommendation is the approval procedure that stands for quality and leads to a consistent place in the total set of the existing regulations.

As a result, over the years the CROW has achieved a status that is appreciated nationally (Wijte, 2019). A CROW Recommendation can also serve as a technical basis for drawing up an assessment guideline (BRL), as a reference document in specifications or in cases where the principle of equivalence is invoked in the context of the building decree. Despite this status, a CROW has no public law status and is therefore not legally required. However, the parties can mutually decide to declare a CROW recommendation applicable, which means that the documents have a private-law status.

7 DISCUSSION

Various parties were interviewed for the research. Many of these parties are part of the same partnership and know each other well. Although this partnership is leading in the constructive 3DCP, it might contribute to interview other parties that work with 3DCP for a more neutral objective result. However, this was probably too much input for the available research time. Also, the research on the legislation and regulations side could have some more focus points. This research only focusses on the standards that are public, universal and is not proprietary. Standards that could potentially be listed in the Eurocode. Another option is to keep the national 3DCP standards quite generic, as written in chapter 6, and companies make their own implementation to provide their own method with a quality mark certification. This is also what often happens in the building environment with specific components. Although this is not common for whole new production methods; it can be interesting to see if a quality mark certification can offer a solution in order to comply with the regulation. More research should be done into this, for example, extended research on the potentials with CE certification or a Komo-certification which are also commonly used in the building environment. Furthermore, an interview with the normalization institute NEN could have led to new insights in which kind of pre-standard suits best to 3DCP and how the interests work with a standards committee.

Also, the proposed intentions were to produce a discrepancy overview that made a distinction what properties which deviated and which not. During the investigation, it became clear that such a distinction is not ideal since 3DCP structures deviate strongly from conventional concrete structures and create many new challenges (e.g. slender layer structural behavior and completely different reinforcement alternatives). Instead, it had much more added value to summarize most all of the known challenges that need to be resolved.

Finally, the intention was to produce an action plan that recommended to all stakeholders what kind of test each stakeholder should perform in order to provide safety assurance. However, not every party performs tests. Moreover, it does not really matter who carries out which tests. The most important part is that a test should be executed scientifically, only then a test can contribute to a proper recommendation, which can then be further experimented.

8 CONCLUSION & RECOMMENDATION

Standards are never a goal on its own. They are prescribed agreements, that serve as a tool between different parties, for example, the client and the contractor. The advantages are that you do not have to reinvent the wheel every time when assuring safety, which can work very efficient. But for now, 3DCP has to be invented because it has never been done before in such a manner. This research aims to identify the current state of 3DCP and how to set future standards. Based on qualitative research analysis consisting of literature and several expert interviews from every relevant field, it can be concluded that several steps are needed from different stakeholders (a more detailed explanation can be found in the actionplan). The developing of 3DCP to standards is a perfect example of the triple helix which consists of a collaboration between the government, academy, and the market. To set standards it is essential to have technological and legislative knowledge in order to write standards. 3DCP is very broad innovation since it asks from every building phase new thinking and new solutions, which also requires the necessary coordination between these parties. To keep standards manageable it is recommended to divide 3DCP in material, structural and executive category. The complexity with 3DCP, however, is that every category is deeply interlinked with each other, so it won't be wise to develop standards for each category individually. Furthermore, standards are most of the time initiated by the market itself. Approach to a standardization institute makes sense when sufficient support and demand for setting standards is realized. One of the most important functions of standards is that they serve as a tool for the license permission authority which is part of the municipality in the Netherlands. When the Eurocode, which describes the structural safety requirement, falls short there can be referred to the equivalence principle. Reference can be made here to standard documents not covered by the Eurocode, for example, an NTA or a CROW recommendation. when no guidelines are written at all, for example with 3DCP, intensive cooperation between government, academic and market are required in order to create a consensus and give permission to build.
Also, when developing new codes, it is important to determine the level of abstraction. A generic code can be open to multiple interpretations and requires more implementation of safety assurance from the contractor. A less abstractive specific code can offer much more grip and keeps safety assurance tangible. However, too specific codes can lead to inhibiting innovation by anchoring to many variables. The roots of 3DCP safety assurance, which serve as the basis for standards, consists of Design By testing which is a part of the Eurocode that serves as the easiest way out, since everyone in the field understands the Eurocode. Design by testing serves as a template to design a structure by performing experiments. By doing more tests and scientific research, more will become known about concrete printing resulting in less testing and more technical recommendations, which can end up in pre-standards and finally serve as standards. 3DCP is strongly in developing, the young method is however still in its infancy and the 3DCP wheel is still being invented further before it doesn't have to be invented anymore in the form of standards.

It is recommended to involve all relevant stakeholders in this development. Setting up standards in the construction industry requires support from all sides: academic, market and government. For the transition to phase 2 of the roadmap, it is recommended that all parties use the 3DCP DBT flowchart protocol to achieve results in the form of pre-standards. Then it will have to be determined what the abstraction should be of an upcoming standard in the next phase. It is then recommended to seek affiliation with an independent standard organization in phase 4.

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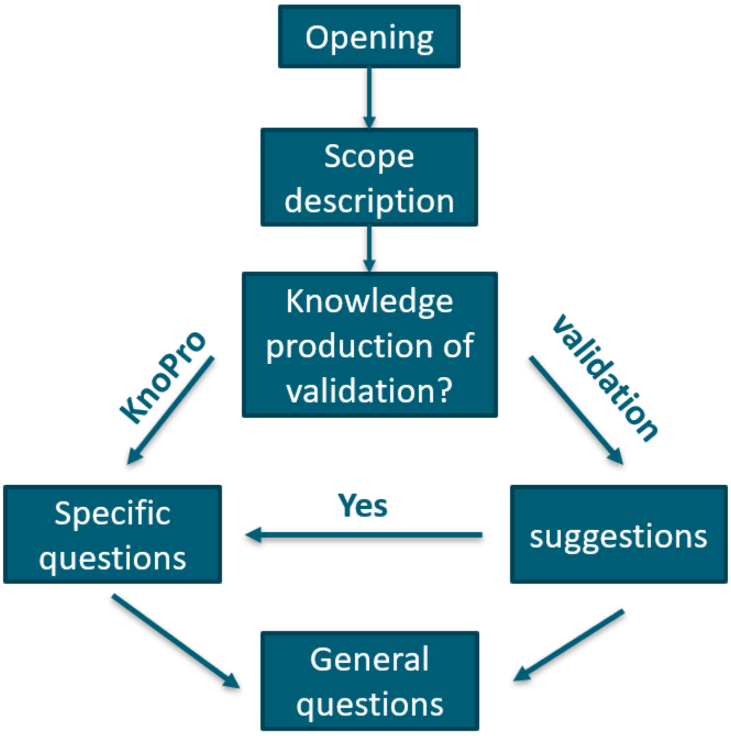
10 APPENDICES

Appendix A: Interview Setup

During the interview, the schedule below is followed. First, the interview was introduced with a scope description of the research. Then the interview was or to produce knowledge or to validate choices that have been made during the research. When there was a suggestion, specific questions were asked in order to produce sufficient argument for the suggestion. When the interview was being performed in order to produce knowledge (knopro), specific prepared questions were asked. Most of the time the interviews ended in general questions related to the sub-questions of the research.



Appendix B: Examples using the 3DCP DBT Flowchart protocol

Example 1: Gemert 3DCP Bicycle Bridge
Opening: October 17, 2017
Remark: First public 3DCP structure that required building permission

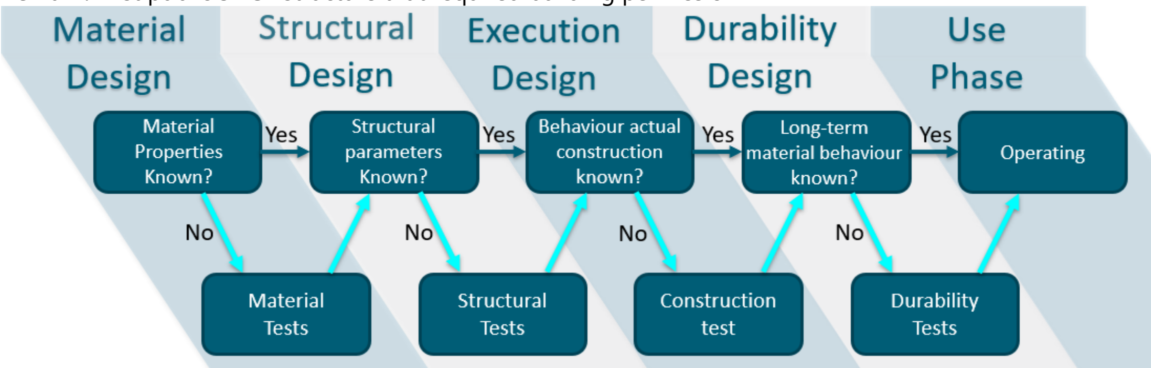


Figure C.1: 3DCP DBT flowchart implementation Gemert

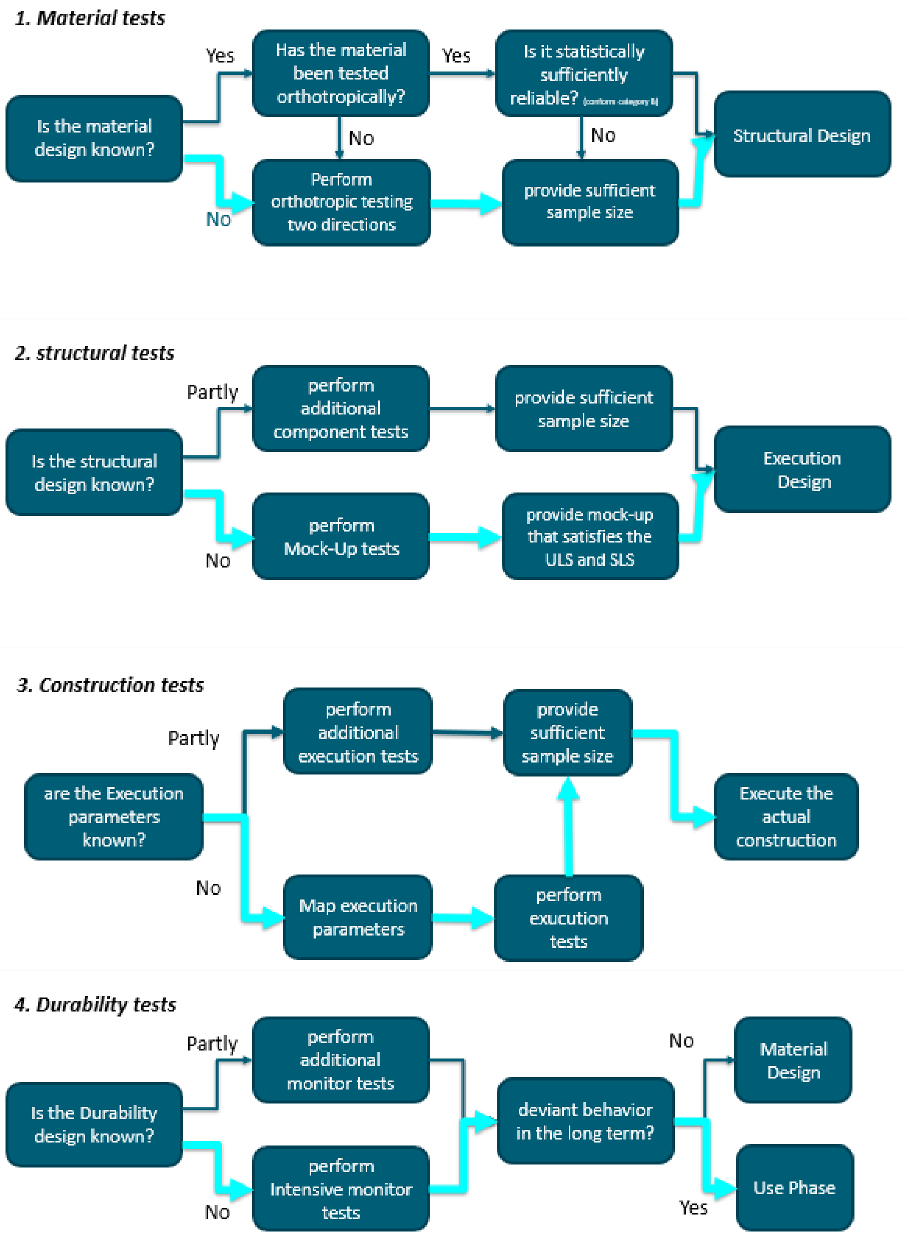


Figure C.2: 3DCP DBT tests flowchart implementation Gemert

Example 2: 3DCP Bridge Noord-Holland
Opening: end of 2019
Remark: First 3DCP bridge that does not include a mock-up test, and therefore performs specific component test.

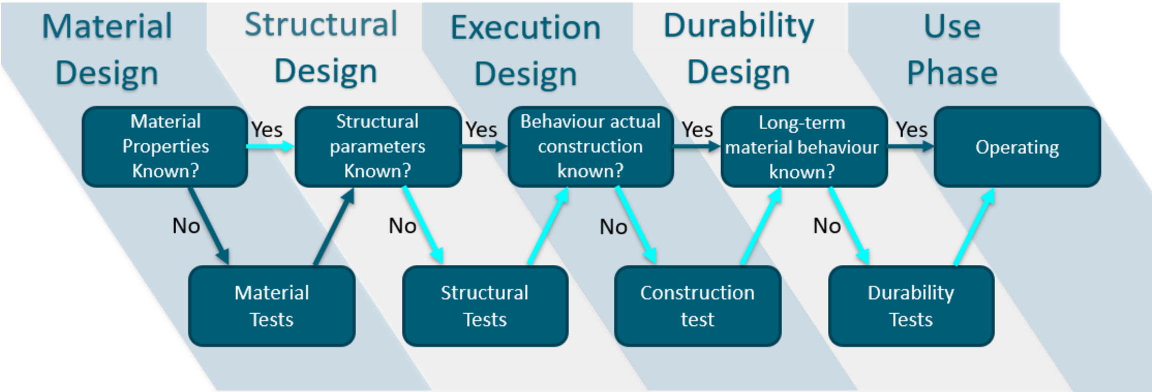


Figure C.3: 3DCP DBT flowchart implementation Noord-Holland

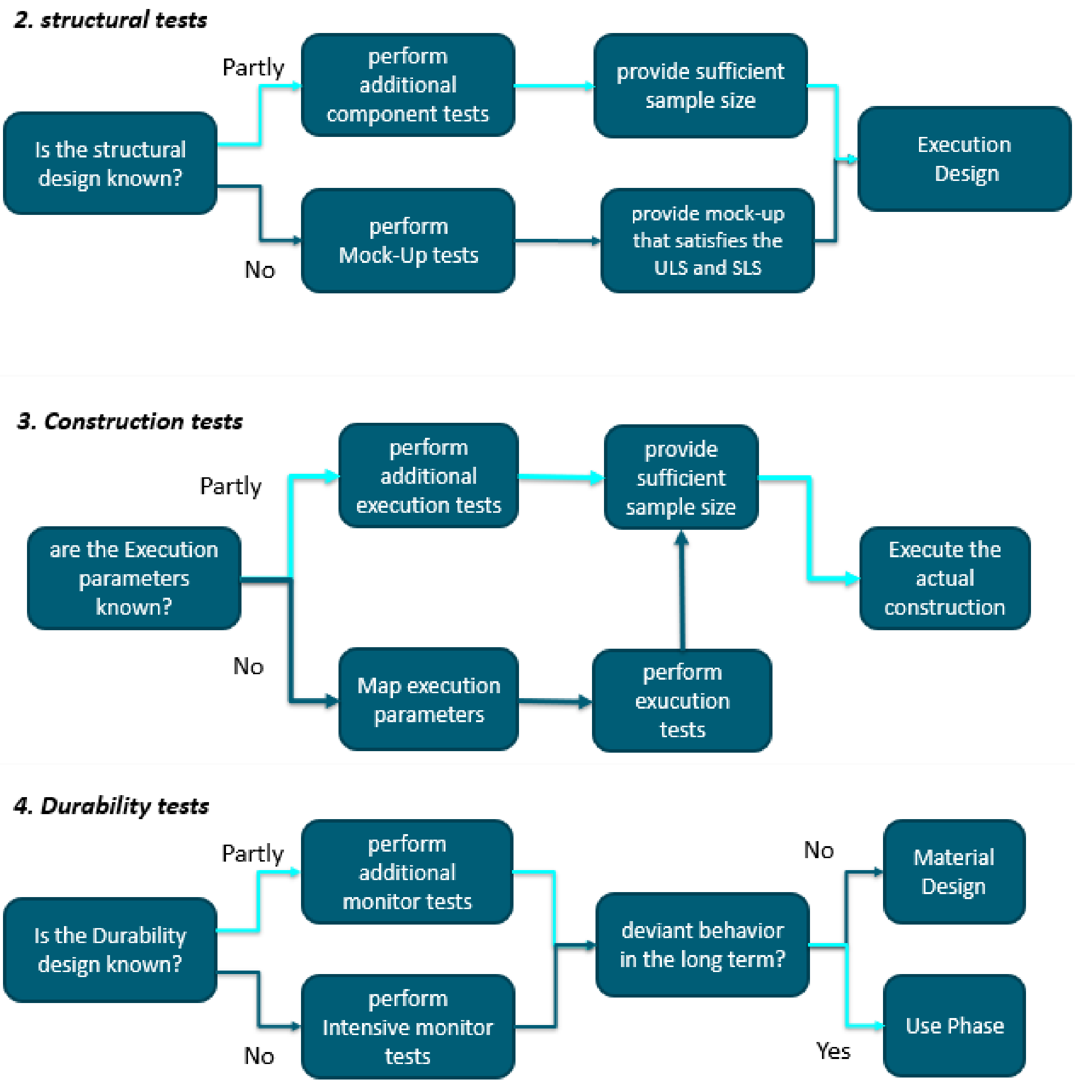


Figure C.4: 3DCP DBT tests flowchart implementation Noord-Holland deze tekst laten staan i.v.m. laatste pagina berekening, wordt niet geprint