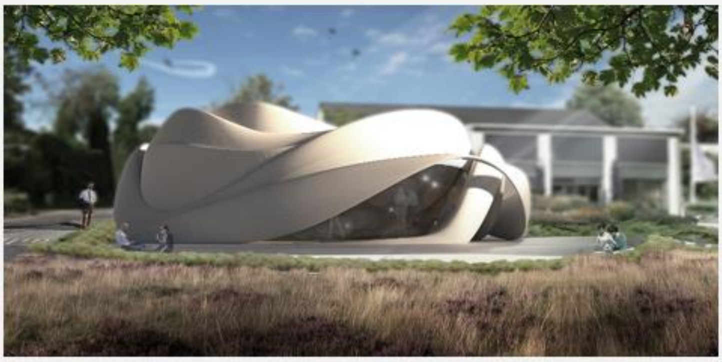
GOVERNING CONSTRUCTION PROJECTS IN WHICH 3D PRINTING IS APPLIED

An integration of traditional project governance, product design and innovation







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Preface

The process of conducting this research shows strong similarities to the 3D printing projects that it aimed to investigate. It involved many experts from different disciplines and industries, lots of initial unknowns, and was highly iterative. The lessons I learned therefore, are interestingly similar to what is required to bring 3D printing technology forward. Skills to manage uncertainty, looking across industry boundaries and disciplines, deal with the resulting conflicting perspectives, and bringing them together in a final deliverable. I think this approach embodies the spirit and added value of the MSc Construction Management and Engineering, and have worked on this project with great enthusiasm.

I would like to thank my committee members for their active support, the experts in Arup who were happy to share their expertise with me, and all interviewees that enthusiastically shared their vision and perspectives.

Henriette, thank you for introducing me to this fascinating topic. Throughout the research you continuously exposed me to new ideas which allowed me to see the bigger picture of what 3D printing might mean for the construction industry. Understanding why and how my research was contributing gave me a lot of motivation.

Jeroen, I enjoyed working with you a lot due to our conversations, your enthusiasm and way of providing feedback. You encouraged me to take charge of my project, and gave feedback in a way that empowered me to build on my own ideas. Particularly in the initial phases when I was in an ocean of different perspectives this was extremely helpful and motivating.

Marcel, thank you for the clear advice during the formal meetings. You added a sharp critical eye to the direction of the overall project, and gave very clear feedback that was understandable. Your genuine interest in my personal opinion on the topic encouraged me to develop my individual perspective between the many experts I encountered.

Rinke, I appreciate the time you made for supervising me during the final stages of the research. Your feedback was always very helpful, clear and understandable. You encouraged me to think critically about my conclusions and how the different aspects of the research fit together.

Foteini, the many conversations we had really helped to structure my thoughts. You were very approachable and provided clear feedback, particularly from a methodological point of view.

Executive Summary

Introduction
3D printing is a manufacturing technology that is rapidly developing. Key differences to traditional manufacturing methods are that highly complex objects can be manufactured at lower cost and that the same (automated) manufacturing process can be used to manufacture a wide variety of objects. Its first mature applications can be seen in the aerospace and automotive industry, where it is used to rapidly manufacture small scale prototypes and tools. Driven by large private and public capital investments, a transition towards manufacturing end products is now being made. The advantages of applying this manufacturing technology include integrated products which require little assembly, weight reductions, increased functionality, increased manufacturing flexibility, shorter lead time of new products, and a simplified supply chain.

In the more conservative construction industry the technology is in a research and prototyping stage, though the first construction projects in which it is applied are emerging. These projects can be classified in two main scenario's:

1) A construction project in which 3D printed components are applied
2) A building in which the majority is 3D printed

In scientific literature little is known about how to govern such projects. The objective of this research is to fill this knowledge gap, by designing a project governance structure for both scenario's. Project governance is defined as the collection of processes and methods to successfully steer projects. Changes from the governance of traditional construction projects are expected because 3D printing introduces new organizations, roles, and activities. Additionally, it requires close collaboration between many disciplines, where a traditional construction project is fragmented. The main research question is therefore stated as follows:

"What is the impact of large scale freeform 3D printing on the governance of construction projects?"

Project governance structures for both application scenario's are designed for the phases inception to construction. (excluding operation and maintenance). The governance structure for the first scenario in which 3D printed components are applied is valid for the current situation and is fully operationalized. The governance structure for the second scenario in which the majority of the building is 3D printed is designed for the future and therefore explorative and generically described.

Research methodology
A broad, empirical, qualitative, practice oriented approach was chosen. A literature review was first done to evaluate the state of the art of 3D printing and operationalize project governance into its elements. Based on this literature study, an interview framework was created and criteria for case studies were defined. Based on these criteria, 7 case studies in which 3D printing was applied were selected. Qualitative empirical data on the governance elements of these case studies was obtained through conducting interviews with key players involved in the project. Results were analyzed and compared to existing governance approaches for traditional construction projects, product design and innovation. Best practices and challenges were extracted and an analysis was done on the differences to traditional construction projects. Based on these insights, the first governance structure for applying 3D printed components was designed. The results were validated against an expert panel. To obtain data on the potential future development, the panel was asked to react against statements regarding the future development of 3D printing. As a final synthesis, an explorative governance structure for the second scenario in which the majority of a building is 3D printed was designed.

Results
4 case studies suited the first scenario in which 3D printing was used for components in a construction project. Its governance approach was a combination of elements from traditional construction projects, product design and innovation. The similarities to product design include an early involvement of the

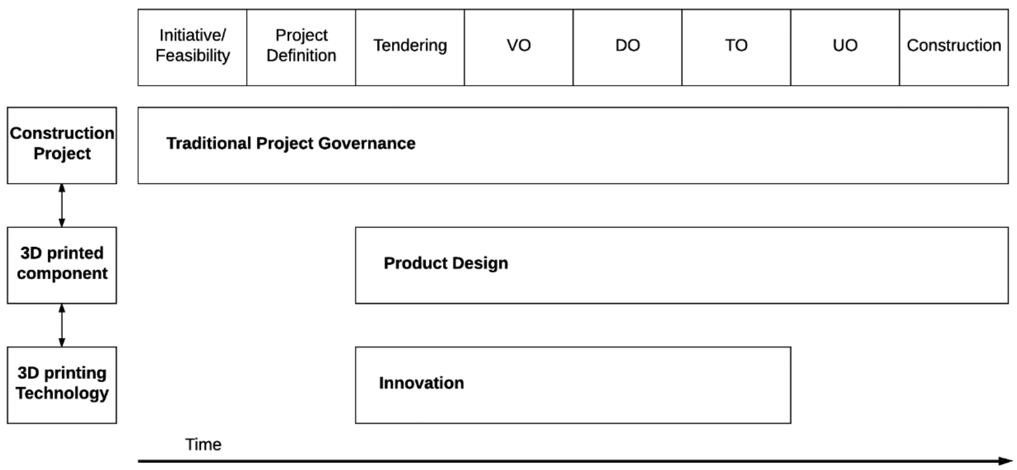
manufacturer, iterations between the design phases, and network relationships between project stakeholders. The different disciplines collaborated closely towards realization of the 3D printed component. Similarities to innovation were the dynamic unstructured process, iterative experimentation with the technology, an ad-hoc style of management, and changing composition of project teams.

2 case studies suited the second scenario in which 3D printing was used to manufacture the majority of the building. Its governance approach was a combination of product design and innovation. From this it can be concluded that the governance of traditional construction projects is not valid for design, engineering and manufacturing of a 3D printed object, regardless of whether it is a small component or a building. Once 3D printing technology is mature in the future, the governance domain innovation will drastically reduce, meaning the governance approach for this type of project will converge to that of product design.

Several differences can be observed when comparing the governance of a project in which 3D printing is applied to a traditional construction project. Standard contracts and design phases are not applicable, there is a central role for the manufacturer, increased uncertainty and risk, an alternative building permit acquisition procedure, additional information system, and new skills are required for project stakeholders. The changes in governance that are therefore required are:

- Adopting a product design approach for the 3D printed object
- Early involvement of the manufacturer
- A new type of contract between manufacturer and project team is required
- A new approach towards communicating progress to higher management layers in the project
- An increased emphasis on risk management
- Early involvement of the municipality to agree on alternative requirements for the grant of the building permit
- Reserving time for education and development of required skills
- Alignment of the different communication systems (2D drawings and 3D models)

Design governance structure 3D printed components
A project in which 3D printed components are applied should be decoupled in three layers: the overall project, the 3D printed component(s) and the 3D printing technology. A fit for purpose governance approach should be used for each individual layer. The layers and their accompanied governance approach are presented in the figure below.



Design governance structure for 3D printing the majority of a future building
An explorative governance structure in which the majority of a future building is 3D printed is designed in this research. In such a project, buildings will be constructed using an industrial approach in which 3D printing is the main manufacturing technology. In the manufacturing process, 3D printing is complemented by other (digital) fabrication technologies, which together form the overall structure. Within the boundaries of the manufacturing capabilities, clients will design their own building using digital design tools developed by the manufacturer. An engineer will then validate whether their design is safe for the unique location of the building, after which the manufacturer will manufacture the building. This would drastically reduce cost and lead time of the building, since the same (optimized) process is used for every project. The whole process is led by one organization. This could be any organization, both within and from outside the construction industry.

This scenario would be difficult to realize with traditional manufacturing technologies. A project now consists of many different types of components (and suppliers), and a relatively large amount of steps is required from initial conception towards actual manufacturing. With 3D printing the amount of components (and suppliers) can be reduced, as well as the number of steps from conception to manufacturing. This reduces complexity and makes it easier for one organization to take responsibility for the whole process. Given the flexibility of its manufacturing process, unique client requirements can be met while using the same manufacturing process. A potential market which is suitable for such a process it is the low cost residential housing market. The outer size is limited and comparable, developments can already be observed in which customers digitally design their own houses, and there is a huge market for it which would justify the large initial capital investments.

Future development 3D printing
3D printing shows strong couplings to other digital technologies and enabling trends in the construction industry, which will develop independently of 3D printing. The most important are BIM, the integration of the project value chain and the R&D done by the aerospace and automotive industry. Due to the conservative nature of the construction industry and the low maturity of the technology, little adoption of 3D printing is expected in the short term (0-2 years). In the medium term (2-5 years) both scenarios are expected to be introduced in the construction industry, starting with the application of 3D printed components.

Recommendations
Clients considering whether 3D printing has value are recommended to read the conclusions of this report and conduct a feasibility study before deciding to apply 3D printing.

Practitioners aiming to apply (or are applying) 3D printed objects are recommended to use a product design approach. If a 3D printed component is applied in an overall construction project they are recommended to apply the operationalized governance structure outlined in this research as a starting point on which detailed allocation of responsibilities can be based.

Visionary organizations aiming to use 3D printing for the majority of a building are recommended to develop larger business cases with their developed technology instead of only applying 3D printing for one project. The second scenario outlined in this research provides an example for this.

Open innovation models are recommended to be applied to drive the adoption process for 3D printing. Innovators within existing firms should be encouraged to form partnerships with universities and organizations outside the construction industry, to fully exploit the potential of 3D printing.

Recommendations for further research are to develop the explorative governance structure outlined in this research in more detail by creating a proof of concept, and to refine the operationalization of the governance structure for the application of 3D printed components by validating it against mature case studies.

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1 Introduction

We live in an exciting time, where new digital technologies are emerging that could redefine the businesses we work in, the societies we live in, and the world as we see it today. The total societal effect of digitalization is referred to as digital transformation. (Khan, 2016) This research takes a closer look at how one of these digital technologies, 3D printing, could impact the traditionally conservative construction industry.

The reason it can be of value is because it could deal with the industry's current challenges like a relatively small increase in productivity and digitization, (Agarwal, Chandrasekaran, & Sridhar, 2016) worker health and safety (Buswell, Soar, Gibb, & Thorpe, 2007) and frequent budget overruns. (Flyvbjerg, Skamris, & Buhl, 2003) It could also provide solutions to future challenges like sustainability, an increased project complexity, and an expected shortage of skilled labor. (Agarwal et al., 2016) 3D printing for the construction sector is currently at a research and prototyping stage (IDEA Consult, AIT, VTT, CECIMO, 2016). It is undergoing rapid development, driven by large public and private investments (Clough, Rolander, & Rothman, 2016). The first applications for the construction industry are being brought to market, and the first projects in which they are applied are emerging.

The transition from research to practice however is not easy to make. Due to its small number of mature examples, little is known on which activities are required to successfully apply 3D printing in functional construction projects, and how responsibility for these activities will be allocated to the new and existing actors. A change from traditional project governance is expected due to several reasons:

- 3D printing introduces new organizations and roles in the project value chain, which will have to collaborate with existing organizations.
- 3D printing requires additional activities in the construction project, and potentially make existing activities redundant.
- New interfaces between existing and new activities might emerge.
- 3D printing requires an integrated holistic design process, where the traditional process is vertically en horizontally fragmented.

The purpose of this research is to design a governance structure for newly built construction projects in which 3D printing is applied, by analyzing seven case studies, comparing the observed governance to that of a traditional project, and designing a new governance structure for two scenarios:

1) A current project in which a number of 3D printed components is applied
2) A future project in which the majority of the building is 3D printed

This report has the following structure. The research objective, scope, relevance and questions are first further elaborated in chapter 2. The methodology that was used in the research is then visualized and elaborated in chapter 3, which consists of a literature study on project governance and 3D printing, interviews with key players from seven projects in which 3D printing is applied, analysis of results, and designing two generic governance structures. The remainder of the report presents the outcomes of these individual steps, starting with the literature study results in chapter 4 and 5. Chapter 4 evaluates the state of the art of 3D printing, by presenting projects in which it is applied, opportunities, challenges, and the two scenarios for which governance structures are designed. Chapter 5 operationalizes project governance, by defining the term and breaking it down into its individual elements. The chapter concludes with starting points for the governance that is expected in the case studies, by presenting existing governance models of traditional construction projects, product design and innovation. Chapter 6 presents the observed governance of the seven case studies in terms of individual governance elements and the identified governance models in the fifth chapter. Current differences between the observed governance in the case studies and the governance of a traditional construction project are discussed in chapter 7. In chapter 8 an operationalized governance structure is presented for the first scenario in which a project in which a number of 3D printed components is applied. Chapter 9 describes the future development of 3D printing and presents a governance structure for the second scenario in which the majority of a building is 3D printed. Conclusions and recommendations are given in chapter 10. A discussion of the results and methodology is presented in chapter 11.

Reading guide

Due to the extensive nature of the report, readers are recommended to read the report in the following order. The general conclusions in chapter 10 provide an initial high level overview and the main points of the research. The discussion in chapter 11 describe the significance of the research compared to the existing body of knowledge. Paragraphs that are significant in the starting points for the case studies are paragraph 5.1, which operationalizes project governance, paragraph 5.5 which presents an overview of the identified governance domains, and paragraph 4.6.5 which elaborates on the future development scenario's for which governance structures were designed. Paragraph 8.2 presents the high level overview of the governance structures for components, where paragraph 9.3 presents a high level description of the explorative governance structures for a future building in which the majority is 3D printed.

Practitioners interested in the empirically observed governance of the case studies can study chapter 6, which provides a detailed description of the phases, activities, roles and responsibilities. Visionary organizations considering to develop 3D printing products or services are recommended to read chapter 4 and 9. Readers interested in the 2017 developments around 3D printing are referred to paragraph 4.6.4 and appendix A and B.

2 Research Objective and Questions

The objective of developing a project governance structure for projects in which 3D printing is applied is elaborated in this chapter (2.1), by specifying the research scope (2.2), the research questions (2.3) and what its relevance is to practitioners and the scientific community (2,4).

2.1 Research Objective

The objective of this research is to develop a project governance structure for newly built construction projects in which 3D printing is applied for the lifecyle phases initiative to construction, by collecting information on the governance of projects in which 3D printing is applied and then designing a new generic project governance structure based on their challenges best practices. This is done for two scenario's:

1) A current project in which a number of 3D printed components is applied
2) A future project in which the majority of the building is 3D printed

2.2 Research Scope

This paragraph further elaborates and specifies the underlined terms project governance structure and construction projects in which 3D printing is applied. When the reader encounters the terms project governance structure or construction project in the following chapters, the scope as discussed below is implied.

Project governance structure
For an elaborate operationalization of project governance, the reader is referred to paragraph 5.1. The following elements are included in the project governance structure of this research:

- Organizations
- Roles and responsibilities
- Lifecycle phases (from inception until and including construction)
- Key activities

The project governance is analyzed on two levels: that of the overall construction project and that of the 3D printed component. The level of integration between these two levels depends on the percentage of the building that is being 3D printed.

Construction projects in which 3D printing is applied
3D printing can be applied to a wide variety of construction projects. Characteristics of these construction are further elaborated in paragraph 4.4.

The scope of this research will contain construction projects with the following characteristics:

- Functional
- Newly built
- Freeform
- Product and building scale

Functional refers to the requirement that the project provides a function in public space and is open to the public. This criteria is chosen because though a lot of (technical) knowledge is available through research projects and artefacts exhibited at conferences, little is known on how to apply it in a real construction project.

Newly built projects mean that the project concerns a newly built structure. Renovation projects are excluded from the scope of this research, due to the lack of available data.

Freeform means that the 3D printed objects have a high degree of complexity. It is one of the philosophies in 3D printing, as opposed to the more standard rectilinear approach. This criteria is chosen because it offers something genuinely new to the construction industry, complex shapes that can be functionally optimized in the design phase. Freeform components are also expected to have the largest impact on project governance.

Scale of the 3D printed elements is on a product or building level. Applications that exist on a material scale are not considered in this research. The technological maturity of these applications are at a too low maturity to find applications in construction projects. Secondly and components applied in construction projects are generally large.

2.3 Research Questions

The research objective can be translated to the following main research question:

"What is the impact of large scale freeform 3D printing on the governance of construction projects?"

The main research question can be broken down into several sub questions, which are presented in the table below.

Sub question	Result	Answered in
(1) What does the governance of a project in which 3D printing is applied currently look like? a) What organizations can be recognized? b) What are the roles and responsibilities of these organizations? c) What project lifecycle phases can be recognized? d) What key activities can be recognized?	Description of the governance of seven projects in which 3D printing is applied	Chapter 6
(2) What are currently the differences between the governance of a project in which 3D printing is applied and a conventional project?	Current differences between the governance observed in the case studies and that of a traditional construction project.	Chapter 7
(3) What is a potential governance for a project in which 3D printing is applied? a) What is currently a potential governance structure for a project in which a number of 3D printed components is applied ? b) What is a future potential governance structure for a building in which the majority of its components are 3D printed?	A governance structure for a current scenario in which a number of 3D printed components is applied (chapter 8) An explorative governance structure for a future scenario in which the majority of a building is 3D printed (chapter 9)	Chapter 8 & 9

The first sub question describes the homogenized governance elements of seven construction projects in which 3D printing is applied. Conclusions of what the governance looks like in current practice is written down in a descriptive manner. The results are compared to the existing governance models from traditional construction projects, product design and innovation.

The second sub question describes the current differences between the observed governance in the case studies and a traditional project (as specified in paragraph 5.2).

The third research question presents governance structures both scenario's identified in the research objective. The governance structure for the first scenario will be fully operationalized, based on best practices and challenges observed in the case studies. The governance structure for the second scenario is explorative and therefore described on a general level.

2.4 Relevance

The relevance and value of answering the research question is based on the assumption that 3D printing will continue to develop and mature so that in the future it will be applied in construction projects.

This assumption is supported by the following evidence

- Enabling trends in the construction industry, digital technologies and R&D from the automotive and Aerospace industry (see paragraph 4.6.4) where the technology is more mature. These developments will occur independently from 3D printing, though they make it easier to adopt 3D printing in the construction industry.
- Forecasted market growth, large private players like HP and General Electric entering the market (see 4.6.1)
- The identified opportunities (see paragraph 4.3)
- Mature applications that exist in other industries (like automotive and aviation)
- The first applications specifically for the construction industry are entering the market (see figure 3)

Following this assumption, this research is relevant for both the scientific community and for practice.

2.4.1 Scientific relevance

Existing literature primarily has a technical oriented focus, that helps in moving the technology forward. It is specialized towards individual disciplines and applications. This research complements this perspective by adding a managerial, practical perspective to the existing literature on 3D printing in the construction industry. It meets the specified need for integrators (IDEA Consult, AIT, VTT, CECIMO, 2016) that can facilitate the required holistic design process (Bos, Wolfs, Ahmed, & Salet, 2016) After all, literature states that the challenges in moving 3D printing forward are not merely technical, but also managerial, financial and cultural. (as discussed in paragraph 2.5).

On a more detailed level, it adds to the scientific knowledge through several deliverables. First, a classification system for projects in which 3D printing is applied (see paragraph 4.4), which provides structure to the wide amount of existing case studies and potential applications. Though a classification on production technologies was published during this research (Duballet, Baverel, & Dirrenberger, 2017), a classification on project level does not yet exist. Second, the designed governance structure(s) can be used as an initial framework that can be used for analyzing future projects in which 3D printing is applied from a managerial perspective.

The second governance structure designed in this research presents a scenario which suggests a fundamentally different way to manufacture buildings at a high speed and low cost. Conditions for its adoption in the market are specified, which provide starting points for further research (see paragraph 9.2).

2.4.2 practical relevance

Currently one of the barriers in applying 3D printing is the lack of knowledge on procedures and standards for designing, engineering and manufacturing 3D printed components and integrating them in the overall project, caused by the low maturity of the technology and its applications.

This research creates awareness on the risks and opportunities of 3D printing, and provides structure and guidance on how to apply 3D printing in a construction project. This allows practitioners to make an informed decision on whether to apply 3D printing in their project. If they decide to do so, the designed governance structure presents a qualitative method on how to govern such a project. Best practices and challenges from previous case studies can be used to reduce risk and increase its value.

The second governance structure that was designed provides a visionary organization with starting points to initiate a high risk – high reward product development process to bring the proposed scenario to the market.

3 Methodology

This chapter describes the methodology applied in this research, which is summarized in figure 1. A detailed elaboration and motivation of this methodology is provided in paragraph 3.1 to 3.4 respectively.

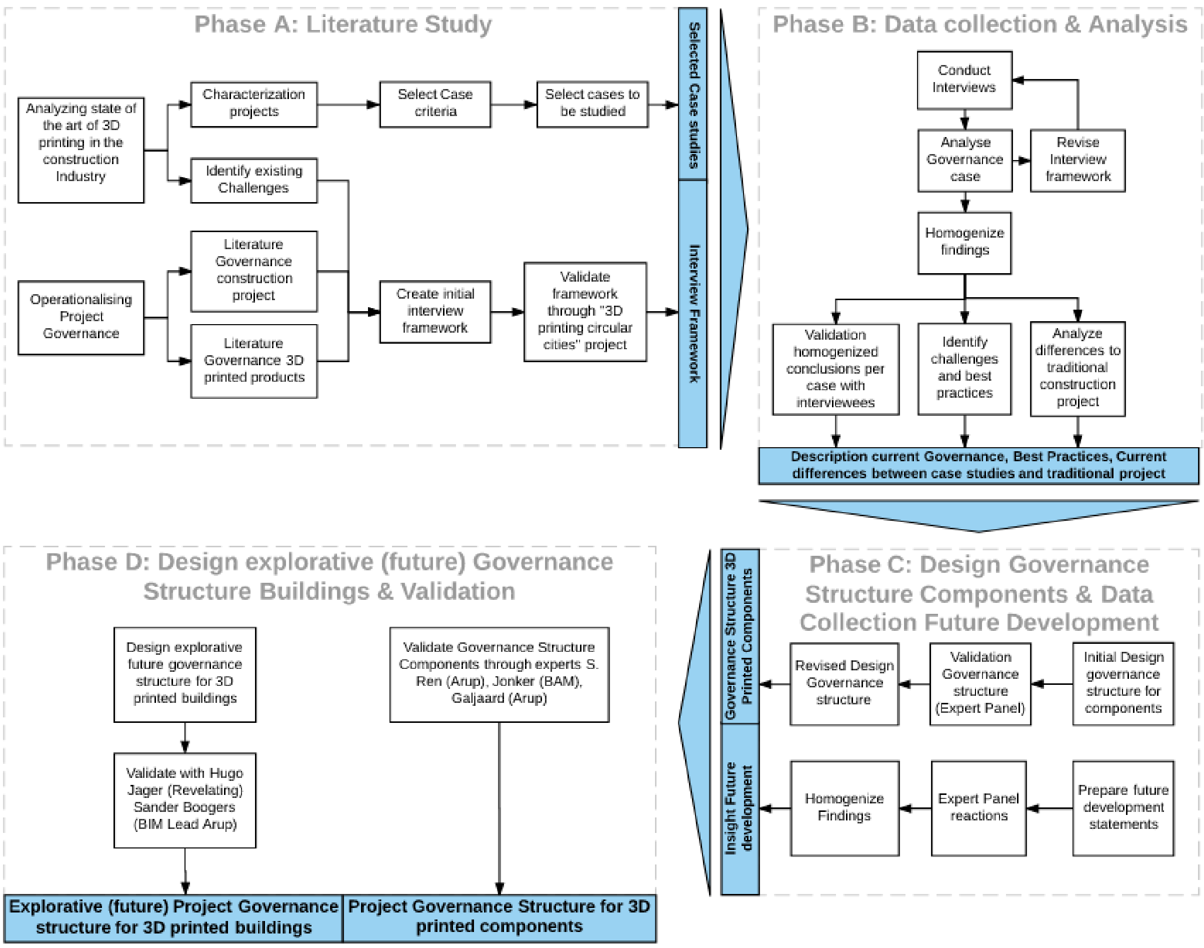


FIGURE 1 RESEARCH METHODOLOGY

3.1 Phase A: Literature Study

The first phase of this research contained a literature study consisting of three aspects: analyzing the state of the art of 3D printing to identify the knowledge gaps, operationalizing the concepts "project governance" and "project in which 3D printing is applied", and preparing an interview framework. In addition to mere desk research, exploratory interviews were conducted, and a workshop of a manufacturer of 3D printed concrete (XtreeE) and the conference "Imprimer le monde" were visited. This was done to complement theory with practical perspectives. Though the following paragraphs seems to indicate a sequential workflow, in practice it was highly iterative.

3.1.1 Analyzing state of the art of 3D printing

The purpose of analyzing the state of the art was to gain a thorough understanding of 3D printing as a technology, what it could mean for the construction industry and identifying the existing (managerial) knowledge gaps. This was accomplished by analyzing the state of the art on the following domains:

- Defining 3D printing and distinguishing it from other digital fabrication technologies
- Opportunities of 3D printing in the construction industry

- Challenges of 3D printing in the construction industry
- Characteristics of projects in which 3D printing is applied
- Future development of 3D printing

The future development was incorporated in this research to increase its practical value for the future, because the technology is rapidly developing and its application will likely change radically in the future. To gain insight on this, literature was consulted on how technologies generally get adopted in markets.

3.1.2 Formulate research objective and strategy

The analysis of the state of the art resulted in the formulation of the research objective to design a project governance structure for projects in which 3D printing is applied. The reason for this decision is that though a lot of literature exists on the technology, little was known about how to deal with non-technical aspects when applying it in construction projects. After formulating the objective, the strategy was determined.

A decision was made for a practice oriented research with an empirical, qualitative and broad approach, with a practical orientation. An empirical approach was chosen because in theory and initial interviews numerous conflicting perspectives were found. Staying close to practice was considered to provide the most objective and reliable results. A qualitative approach was chosen because the technology is at a low level of maturity and little quantitative information is available. A broad perspective was chosen because an initial project inventarisation revealed that projects in which 3D printing was applied had a wide variety of characteristics. An in depth analysis of a few projects would therefore be too project-specific, and findings would be difficult to generalize to projects with other characteristics.

Because of these considerations, case-studies were chosen as the primary strategy for data collection. Information on these case-studies was collected through interviews with key people involved in the project. A survey was considered but not chosen, because this would diminish to get qualitative elaborations on the answers given. The chosen strategy required two additional steps to be done: selecting case studies and creating an interview framework.

3.1.3 Operationalizing "Project Governance" and "Project in which 3D printing is applied"

Project governance was operationalized by breaking it down into its elements (phases, activities, organizations, roles and responsibilities).[1] "A project in which 3D printing is applied" was operationalized by selecting case criteria from the identified project characteristics and finding cases that met this criteria. The initial overview of available case-studies was made through websites (Koslow, 2017) and complemented through Arup and TU Delft's network. For these projects, characteristics were identified (see paragraph 2.4). Through these criteria the initial list was comprised to 11 projects. Key players within the projects were identified and invitations were sent. Because of the limited amount of available case studies, the invitation emphasized the value the research would provide to the interviewee.

3.1.4 Creating an interview framework

To structure the interviews an interview framework was created in parallel to the selection of cases. The ultimate goal of this project was to develop a governance structure for a 3D printing project. An important requirement for the interview framework was therefore that it should include all elements of project governance: Life cycle phases, activities, organizations, roles and responsibilities. Literature was reviewed first to obtain knowledge on each element for traditional construction projects and 3D printed products.

[1] The operationalization to project governance was incorporated during the interviews. At the start of the research, it was still referred to as phases, activities, roles and responsibilities.

Literature on the phases and activities of traditional construction projects was obtained from the STB 2009, which provides multiple levels of detail in phases towards detailed activities. (BNA, NLIngenieurs, & ONRI, 2009). The additional benefit was that the framework was Dutch, so the (mostly Dutch) interviewees have knowledge about the framework. Literature on the organizations and roles was obtained from CIOB's guide to project management (Chartered Institute Of Building, 2014). Literature on the life cycle process of 3D printed products was obtained from the Aerospace industry (Romero-Torres & Vieira, 2016). Literature on the organizations and roles was obtained from a value chain analysis from EY (EY, 2016)

To determine detailed roles and responsibilities, the interview framework contained a RASCI matrix This is an expanded version of the RACI model, which is often *"used for the development of project governance structures"* (Chartered Institute Of Building, 2014). In a RASCI matrix key activities are listed and responsibility for them is allocated to specific actors.

To improve existing practice, specific questions were included on how the project team dealt with often occurring challenges and how the process could have been improved.

Although this framework provided a starting point, it was considered unlikely that a new innovation would fit in a combination of old frameworks. This is why during the research the framework was updated based on the results of the interviews. To validate the first version of the framework, it was used for an interview in a research project. The findings showed that the model was indeed valid, and some improvements were made.

3.2 Phase B: Data collection & Analysis

The purpose of the data collection and analysis was to describe the existing governance of projects in which 3D printing is applied, and to identify the current differences between governance observed in the case studies and traditional projects. At a later stage, the results were compared to existing governance approaches for product design and innovation.

An interview was conducted for 7 out of the 11 selected cases. A multi perspective approach was successfully adopted, by interviewing people from a variety of backgrounds, like innovation consultant (Revelating), 3D Printing service provider (CyBe), structural engineer (Arup), designer and digital fabrication expert (Arup), contractor (BAM) and researcher (the New Raw). The advantage of this multi-perspective approach is that all perspectives can be taken into account when designing the governance structures.

Results were homogenized to compare the results from individual cases and draw conclusions. Because this required an interpretation from the answers provided by the interviewees, a validation was done with interviewees from all cases to verify whether they saw it interpretation as valid. Besides several small comments, this was indeed the case. Through analysis, commonalities, best practices and challenges were identified. These served as input for the designed governance in the next phase. During the analysis of the results, strong similarities were found between the observed governance elements in the case studies and existing governance models on product design and innovation. Literature on these models was investigated and linked to the case studies. Combined with the homogenization, this provided an answer to the first research question.

A second analysis was done to analyze the differences between the observed governance in the case studies and the governance of a traditional construction project. This analysis distinguished between differences that were a consequence of a low technological maturity and differences that were expected to continue to exist when 3D printing as a technology is mature. Results of this analysis provided an answer to the second research question.

3.3 Phase C: Designing a project governance structure for a current project in which 3D printed components are applied

The purpose of this phase was to design a project governance structure for 3D printed components and gain insight in the future development of 3D printing.

Two options for designing the governance structure were considered. The first is a generic governance structure, providing guidelines which can be slightly customized for the unique circumstances of a project. The second option is a process for a case, in which a process is designed for one specific project. Considerations for both approaches are summarized in the table below:

Category	**Evaluation generic process**	**Evaluation process for case**
Validity	Valid for different types of projects in which 3D printing is applied	Only valid for projects with the same characteristics as the case
Practical value	High	Lower
Utilization collected data	Insights from all cases can be integrated	Insights from some cases might be "lost"
Level of detail	Important details might be overlooked	High degree of detail can be achieved

During the literature study, it was found that projects in which 3D printing is applied, have a wide variety of characteristics. During the interviews it was found that these characteristics have an influence on the governance of a project in which 3D printing is applied. This means that if the governance would be designed for one case, it would have limited applicability to projects with different characteristics, diminishing the practical value of the developed governance structure of this research. When a generic governance structure is designed however, the project could be applied to projects with different types of characteristics, increasing its practical value. This is reinforced by the fact that it is not yet clear which characteristics will occur more frequently in the future. Following this evaluation, a generic governance structure was chosen to be designed. The design is based on the commonalities, best practices and challenges observed in the case studies. Best practices were validated in literature, to confirm they value.

Validation

This design was validated through an expert panel meeting, consisting of 3D printing experts, senior project managers, and interviewee's from the cases. The initial plan was to validate the governance structure through presenting the findings and ask whether the interviewees deemed the generic governance structure valid for their individual cases. The reactions from the interviewees would have given insight in the applicability of the generic governance structure to their specific case, and important details that might be missing could be added to the framework. Also, it would provide insight in how hard the translation from the generic governance structure to their specific project is. Due to unforeseen circumstances however, there were four last minute cancellations, all from the interviewed cases. [2] The attendees of the meeting were Foteini Setaki (3D printing researcher TU Delft), Rinke Kluwer (Senior Project Manager Arup), and Shibo Ren (structural designer Arup). Feedback primarily concerned the extent to which the governance structure differed from that of a traditional supplier, and emphasized the importance of distinguishing between the project and component level.

[2] This issue was mitigated in three ways: finding a 3D printing expert in Arup to fill the gap in the meeting, and scheduling individual meetings with the interviewees from two cases (Hugo Jager, Chris Jonker).

Future development
During this expert panel meeting insight was gained on the potential future development of 3D printing, which was required as input for the explorative future governance structure for 3D printed buildings. This was accomplished by preparing several future development statements, related to the transitioning period towards the 3D printed buildings scenario and what the governance of this structure might look like, and noting down the reactions (and discussion) from the panel members. In later meetings, Hugo Jager (Revelating) and Chris Jonker (BAM) also reacted to this set of statements. Reactions were homogenized and input was gained for the future explorative governance structure. Valuable here is that again a wide variety of perspectives were included (contractor, project manager, researcher, engineer, innovation consultant).

3.4 Phase D: Designing an explorative governance structure for a future building in which the majority is 3D printed & Validation

The purpose of this phase is twofold: the second validation of the governance structure of 3D printed components, the design (and validation) of the governance structure for 3D printed buildings.

To improve the reliability of the governance structure for 3D printed components, a second validation was done through meetings with two experts: Chris Jonker (Tender Manager BAM) and Shibo Ren (Engineer Arup), who both have affinity and expertise in applying 3D printing in construction projects. Though they were positive about the results, the graduation committee was interested in a more general picture of why the governance structure was best fit for applying 3D printing, since the governance structure was now quite detailed.

Findings were incorporated and a split was made between the layer of overall project, 3D printed component and 3D printing technology, including a fit for purpose governance approach. This final was again validated through the graduation committee, and Galjaard (Digital fabrication expert Arup). During this final validation, both showed consensus and were positive about the results. Last elements that were added were the identification of interfaces and distinguish what is uniquely differentiating about 3D printing in this new governance structure.

The second explorative governance structure for buildings was designed as a final synthesis of the research. Elements that were used were literature on how innovations get adopted in a new market, the future development statements from the expert panel, and the best practices and future improvements that were obtained in the case studies. Given its explorative nature for a future scenario, it was described in a generic way.

This governance structure was validated through all members of the graduation committee, and later through Galjaard, who showed a general consensus on its validity.

4 State of the art of 3D printing in the construction industry

This purpose of this chapter is to evaluate the state of the art of 3D printing in the construction industry through desk research and exploratory interviews.

First, 3D printing is defined and distinguished from other digital fabrication technologies in paragraph 4.1. Paragraph 4.2 then briefly describes the state of the art of 3D printing in the more innovative aerospace industry. The opportunities for the construction industry are then discussed in paragraph 4.3. In paragraph 4.4 projects in which 3D printing is applied are presented and project characteristics are identified. Existing challenges are mentioned in paragraph 4.5. Finally, in paragraph 4.6, the future development of 3D printing is discussed, based on literature and attendance of the 3D printing conference Amsterdam 2017 (see appendix B for the main insights). The chapter concludes with presenting the two scenario's for which governance structures will be designed in chapter 8 and 9.

4.1 Definition

3D printing is the computer controlled manufacturing of a virtual 3D model into a physical 3D object, through a layer by layer build up of material. Since this sounds very technical, literature is used to elaborate the three underlined aspects mentioned in the definition above. The Lloyd's Register Foundation defines 3D Printing, also known as additive manufacturing, as the "*layer-by-layer build-up of material to create a three dimensional object"* (Lloyd's Register Foundation, 2016) This can be distinguished from subtractive manufacturing methods like milling, as can be seen in figure 2.

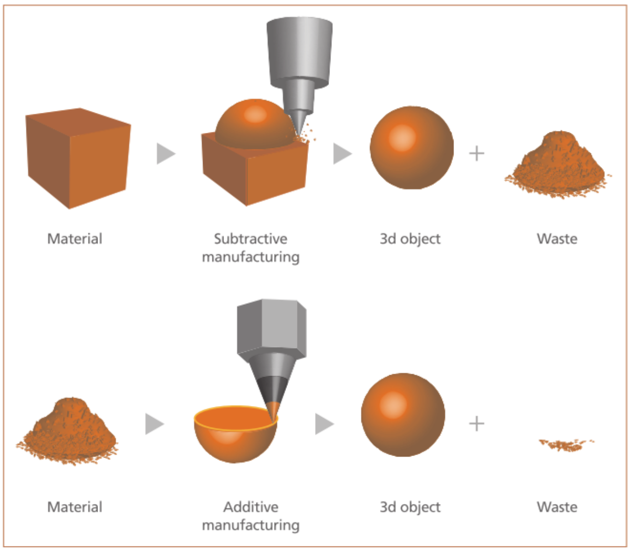
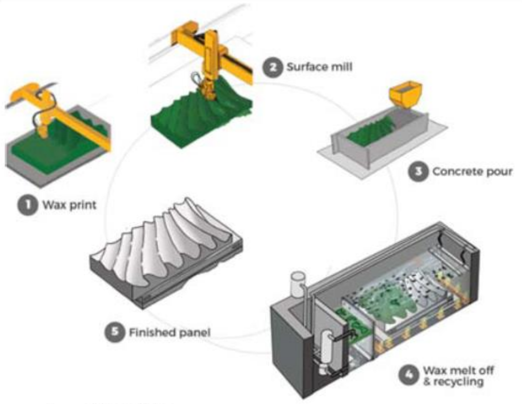


FIGURE 2 SUBTRACTIVE (TOP) AND ADDITIVE (BOTTOM) MANUFACTURING METHODS

Romero-Torres and Vieira define it as "*a process of creating a three-dimensional object or 3D-model from a digital model"* (Romero-Torres & Vieira, 2016), emphasizing that it allows to manufacture a physical object directly from a digital 3D model. As this research focusses on automated 3D printing, it should finally be noted that this process is computer controlled, rather than done manually.

3D printing falls under the umbrella of digital fabrication, which has a variety of definitions in literature. Put simply, it can be defined as: *"computer-controlled manufacturing that either builds a product from the bottom up or cuts away at material to create the product from the top down."* (Schrader, n.d.) Bottom up here refers to additive manufacturing, where top down refers to subtractive manufacturing. In practice, combinations of additive and subtractive methods, so called "hybrid methods" can also be observed. An example is a new manufacturing process by Laing O'Rourke, presented in figure 3. (Gardiner, Janssen, & Kirchner, 2016)

This process includes additive (wax print), subtractive (surface mill), and even casting (concrete pour) methods.



1. Wax print
2. Surface mill
3. Concrete pour
4. Wax melt off & recycling
5. Finished Panel

FIGURE 3 LAING O'ROURKE'S MANUFACTURING PROCESS TO PRODUCE COMPLEX FORMWORK (GARDINER ET AL., 2016)

Another example in this category is the technology Cellular fabrication (C-Fab) recently developed by Branch Technology, which prints the support structure of walls and then sprays insulation and casts concrete to produce a fully functional wall. (Wu, Wang, & Wang, 2016)

When 3D printing is mentioned throughout this research, it refers to both additive and hybrid methods. This means purely subtractive fabrication methods (like CNC Laser Cutting) are not included in this research.

4.2 3D printing in other more innovative industries

Though 3D printing in the construction industry is currently at a research and prototyping stage (IDEA Consult, AIT, VTT, CECIMO, 2016), more mature applications exist in other industries. According to an EY report on 3D printing, 3D printing is currently most applied in the aerospace industry (EY, 2016), as shown in figure 4. The state of the art and best practices of this industry are of value when 3D printing is to be adopted in the more conservative construction industry. The fact that figure 4 does not contain the construction industry highlights the fact that mature applications do not yet existed in 2016.

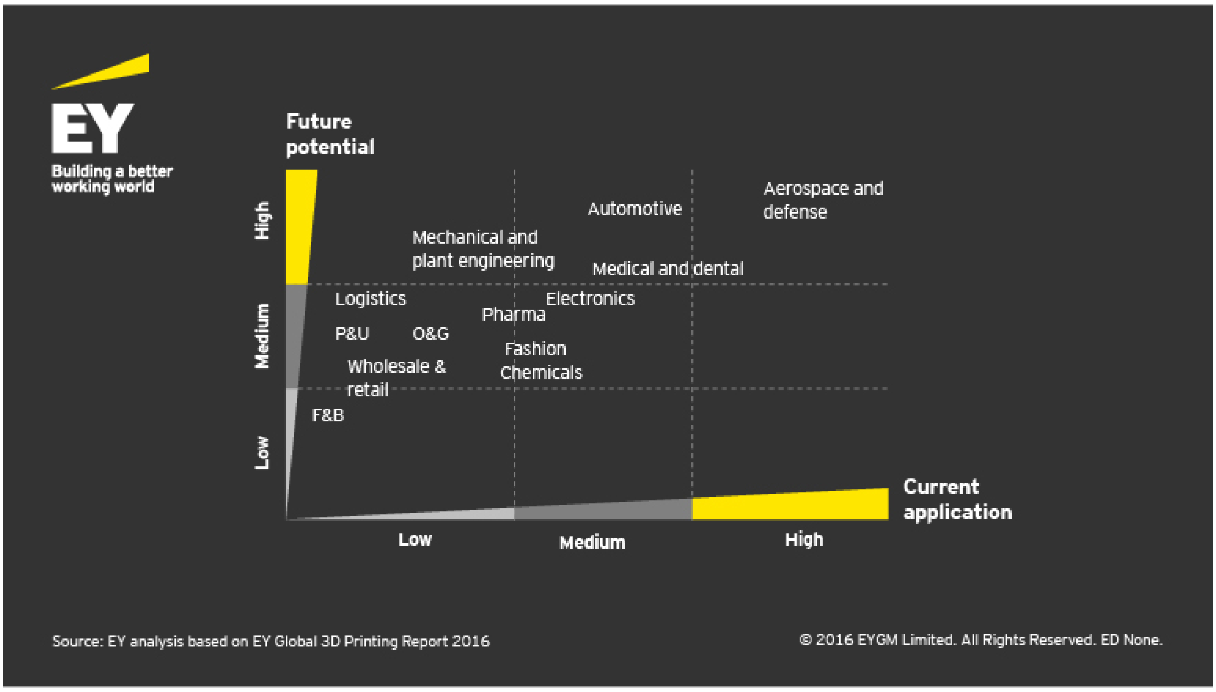


FIGURE 4 FUTURE POTENTIAL AND CURRENT APPLICATION OF 3D PRINTING IN SEVERAL INDUSTRIES (EY, 2016)

Practical applications

Three main applications in the aerospace industry are rapid prototyping, rapid tooling, and rapid manufacturing. (Romero-Torres & Vieira, 2016) Currently a transitioning is occurring from producing small scale objects (rapid tooling, rapid prototyping) towards end product manufacturing (rapid manufacturing).

Boeing for example, plans to receive FAA certification the production process of their (lightweight) 3D printed components for a new line of airplanes by the end of 2017. They expect to reduce production cost by 3 million per plane through 3D printing of titanium aircraft components. (Vincent, 2017)

Opportunities

3D printing offers several opportunities for the aerospace and aviation industry. Firstly, cost of aircraft components can be reduced. Through topological optimizations, material is only put where needed. This results in less raw material usage (which are generally expensive). Also, it reduces the weight of the overall airplane, which again results in less fuel usage (saving 1 kg in weight results in 3000 euros of fuel savings per year). (Romero-Torres & Vieira, 2016) The second big advantage is that 3D printing reduces the lead time of new or replacement components (80% compared to traditional methods), resulting in reduced time to market of new aircrafts and less downtime of the aircraft during maintenance. (Romero-Torres & Vieira, 2016) Third, durability and performance of the components can be increased through part consolidation. Normally complex parts have to be assembled from several conventionally manufactured components. The assembly points are often weak spots. These weak spots can be removed when a component is manufactured monolithically (in one piece) through 3D printing. Fourth, logistical complexity can be reduced. The supply chain of the aerospace industry currently consists of a lot of organizations. Applying 3D printing can result in more simple supply chains by moving the manufacturing closer to the place where the object is needed. (Romero-Torres & Vieira, 2016) This results in less requirements for transportation and reduces logistics cost and complexity. It also allows for less (low volume, high cost/lead time) inventory when elements can be produced on demand. (Romero-Torres & Vieira, 2016)

4.3 Opportunities

It is clear that 3D printing offers significant advantages for the aerospace and aviation industry, but why is it interesting for the construction industry? This paragraph provides an answer to this question, by listing the opportunities 3D printing presents for the construction industry. These are:

- Manufacturing of complex shapes at lower cost
- Product integration
- Mass customization
- Sustainability
- Automation
- Construction time

Manufacturing complex shapes at lower cost
3D printing produces highly complex shapes at lower cost than conventional methods of production. (Gardiner et al., 2016) This allows for (complex) functionally optimized shapes geometries to be manufactured, which could lead to increased structural, thermal, or acoustic performance of building components. (Labonnote, Rønnquist, Manum, & Rüther, 2016) Optimized elements also need less material to provide the same function, resulting in weight reduction of the elements. This in turn could lead to decreased dimensioning of other elements like foundations, leading to significant weight (and cost) reductions in the overall structure. An example is a research by Arup on the steel nodes for a landmark in the Hague. (see figure 5) After several optimization iterations, the design team was able to reduce the weight of the complex steel nodes by 75%, resulting in a 40% weight reduction for the overall structure. (Galjaard, Hofman, Perry, & Ren, 2015)

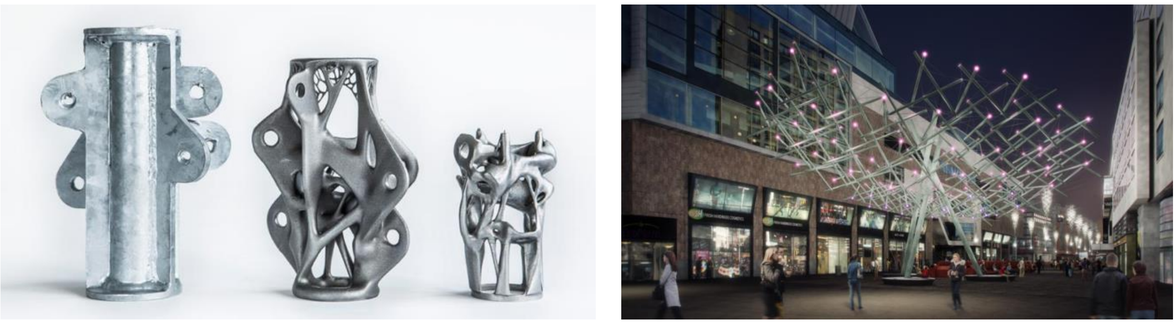


FIGURE 5 STRUCTURALLY OPTIMIZED STEEL NODES (GALJAARD, HOFMAN, PERRY, ET AL., 2015)

Product Integration
Complex geometries normally have to be assembled from many small components which are fabricated independently from each other. With 3D printing, these components could be manufactured monolithically, reducing the number of components and the number of steps and organizations involved to manufacture it. Since construction projects consist of many complex elements, this product integration might be an opportunity to greatly simplify the project supply chain and on site logistics.

Mass customization
3D printing can be economically attractive when a large amount of unique elements is required for a project, because it allows elements to be customized at little additional cost. This opportunity is referred to as mass customization, in contrast to the currently used predefined shapes to decrease the cost of production. (Strauß & Knaack, 2016)

Figure 6 illustrates this concept, by presenting cost per unit for both additive and conventional manufacturing. If a change to a product is required in a conventional production process, the molds, processes have to be adjusted, resulting in an initial large investment. As more products are being manufactured, the overall cost per unit will go down. For 3D printing however, adjusting a final product merely requires an adjustment in software, resulting in the same cost per unit, regardless of the amount of units produced. This means that the option becomes cost effective when a large number of small batches of unique elements is required for a project. (Galjaard, Hofman, Ren, & Perry, 2015)

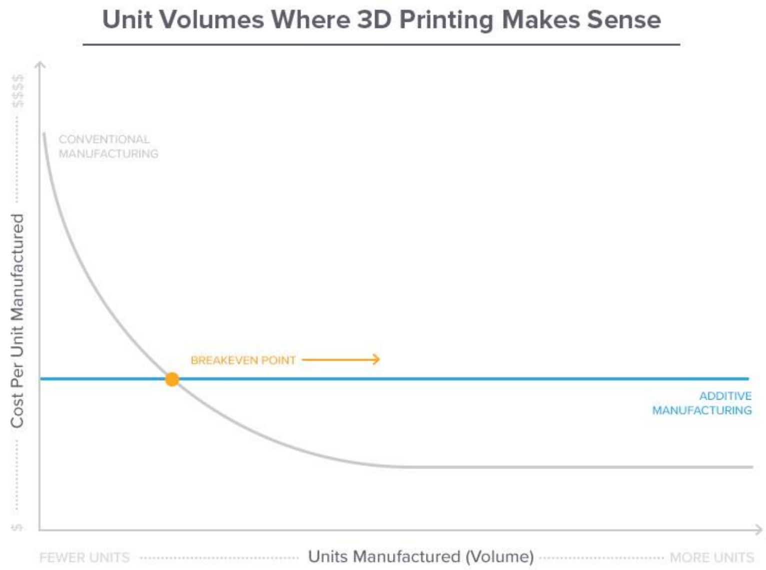


FIGURE 6 UNIT VOLUMES WHERE 3D PRINTING IS COST EFFECTIVE (DÁVID LAKATOS, 2017)

Sustainability
Elements that are functionally optimized have a higher function/material ratio, that could result in less usage of raw material, leading to lower carbon emissions. When additive manufacturing is applied on site, material is translated into the final structure in a direct manner, without the need for tools or formwork. (Ford & Despeisse, 2016) This results in less waste throughout the whole supply chain. A second advantage is the re-usage of waste materials from old buildings, which is already possible for plastics. Examples are the 3D-Printing in the Circular City" project (discussed in paragraph 6.1) and the 3D printed facades that DUS architects and DeMeeuw have announced to develop. (DeMeeuw, 2017)

FIGURE 7 3D PRINTED CIRCULAR FAÇADE BY AECTUAL AND DEMEEUW (DEMEEUW, 2017)

This presents an interesting relation to the trend towards a more circular economy, that aims to reduce the amount of waste by re-using materials and components (in contrast to the produce-use-dispose philosophy).(Arup Foresight, 2016) At the moment, a large amount of waste is created when buildings are at the end of their lifecycle at have to be demolished. Providing a method to transform this waste into new construction materials that can be used to 3D print new buildings would be a game changer. A note should be added here that complete re-use of existing components will be more challenging for 3D printed freeform structures, because the element is customized and can have an integrated functionality

(Bos et al., 2016). This makes it unlikely that the same element could be used in new unique circumstances of a new project. Processing the materials will be required, which can be an energy intensive process.

Automation
Introducing automation in the construction phase deals with several challenges for the construction industry described in chapter 1, like an expected shortage of skilled workers and worker safety. Furthermore, it could increase productivity in terms of value added per hour worked, which has remained stagnant for a long period. (Agarwal et al., 2016) Because construction is a very cost sensitive industry, the opportunity to reduce labor cost in a project might be an important driver in future applications.

Time
3D printing could also reduce construction time. (Wu et al., 2016) Particularly for unique shapes with a high complexity, assembling individual pieces or making complex formwork can be time consuming activities. Applying 3D printing could therefor reduce the cycle times for new batches of concrete.

4.4 Project characteristics

Projects in which 3D printing is applied have a wide variety of characteristics. An initial list of these characteristics is presented in table 1. The characteristics were obtained based on analysis of a case inventarisation of all projects in which 3D printing is applied in the construction industry. The reason these characteristics were identified is because they might differentiate the type of governance that will be observed in the case studies. Secondly, it is used to define case criteria for the selection of case studies. This paragraph will elaborate on the identified characteristics by listing the projects to which they apply.

Form Freedom	Project Type	Element Scale	Material	Printed Elements	Location of production	Printing Style	Employed Technology
Rectilinear	Research	Material	Concrete	Stuff	On Site	"Inside the box"	FDM
Freeform	Artefact	Product	Steel	Space	Off Site	"Outside the box"	SLS
	Functional	Building	Plastic	Structure			Binder Jetting
			Nylon	Skin			
			Stone	Services			
				Site			

TABLE 1 CHARACTERISTICS PROJECTS IN WHICH 3D PRINTING IS APPLIED

Form freedom
A distinction that is important to make is the degree of form freedom that can be achieved. The ability to generate complex shapes is a key opportunity for 3D printing. A large number of the mature projects however, do not utilize this form freedom, but rather produce conventional rectilinear shapes with new production methods.

Bos et all refer to these different approaches as optimizing production and optimizing performance. (Bos et al., 2016) Optimizing for production focusses on printing with a high speed at low costs. Examples are projects by the Chinese firms HuaShang Tengda and Winsun (see figure 8). Optimizing for performance entails the production of complex shapes to increase their functionality. Mature examples in this category are found much less in practice but are currently emerging (see figure 9).

Figure 8 Rectilinear (Winsun's 3D printed Villa (Kira, 2015), ApisCor's printed House (Corboy, 2017))

Figure 9 Freeform (Vergaderfabriek (picture received from interviewee Jager), MX3D Bridge (Laarman, 2017))

Project Type

A distinction can be made between research projects, artefacts, and functional projects. Research projects are done at universities with the aim of researching and developing 3D printing technology. These do not necessarily provide a direct public function. Artefacts do provide a direct function to the public, but this is often merely aesthetic. Functional projects are the projects that are open to the public and serve a function other than merely aesthetic value. In other words, it's applied in real construction projects. At the moment of writing, mature examples of projects in which 3D printing is applied are mostly research oriented or artefacts. Functional projects are emerging. Examples in each category can be found in figure 10.

Figure 10 3D-Printing in the Circular City (research) (picture obtained from interviewee), XTreeE pavilion (artefact) (XTreeE, 2016), Post in Aix en Provence (functional) (XTreeE, 2017)

Element Scale

Different scales can be recognized for 3D printed components. Though size is somewhat subjective, a distinction can be made between material (small), product (medium) and building (large) scale. Though little applied, material scale refers to the local adjustments in structure of the material (for example lattice structures). This can reduce weight, and can also be used to influence the mechanical properties (see appendix B). Product scale refers to medium sized objects, like nodes or small ornaments in a building.

Building scale refers to elements with a large size, like walls and columns. Figure 11 shows examples in each category.

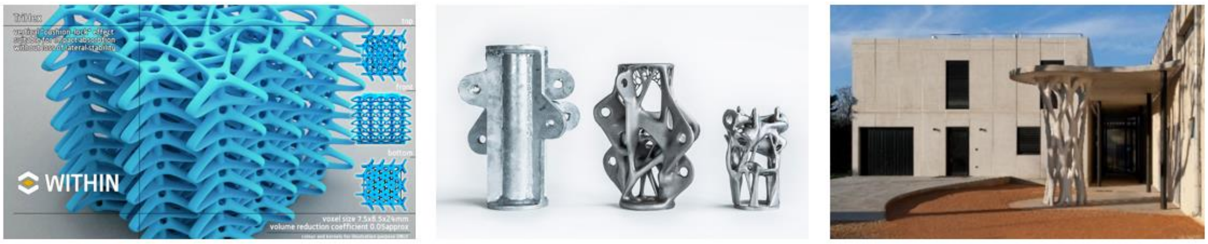


FIGURE 11 LATTICE STRUCTURE WITHIN (MATERIAL SCALE) (GALJAARD, HOFMAN, PERRY, ET AL., 2015) OPTIMIZED STEEL NODES (PRODUCT SCALE) (GALJAARD, HOFMAN, PERRY, ET AL., 2015), POST IN AIX-EN-PROVENCE (BUILDING SCALE) (XTREEE, 2017)

Materials

Recent developments have made it possible to 3D print in a variety of materials that can be relevant for construction, like steel, concrete, stone and plastics. Figure 12 gives examples of projects in which these materials are being applied.

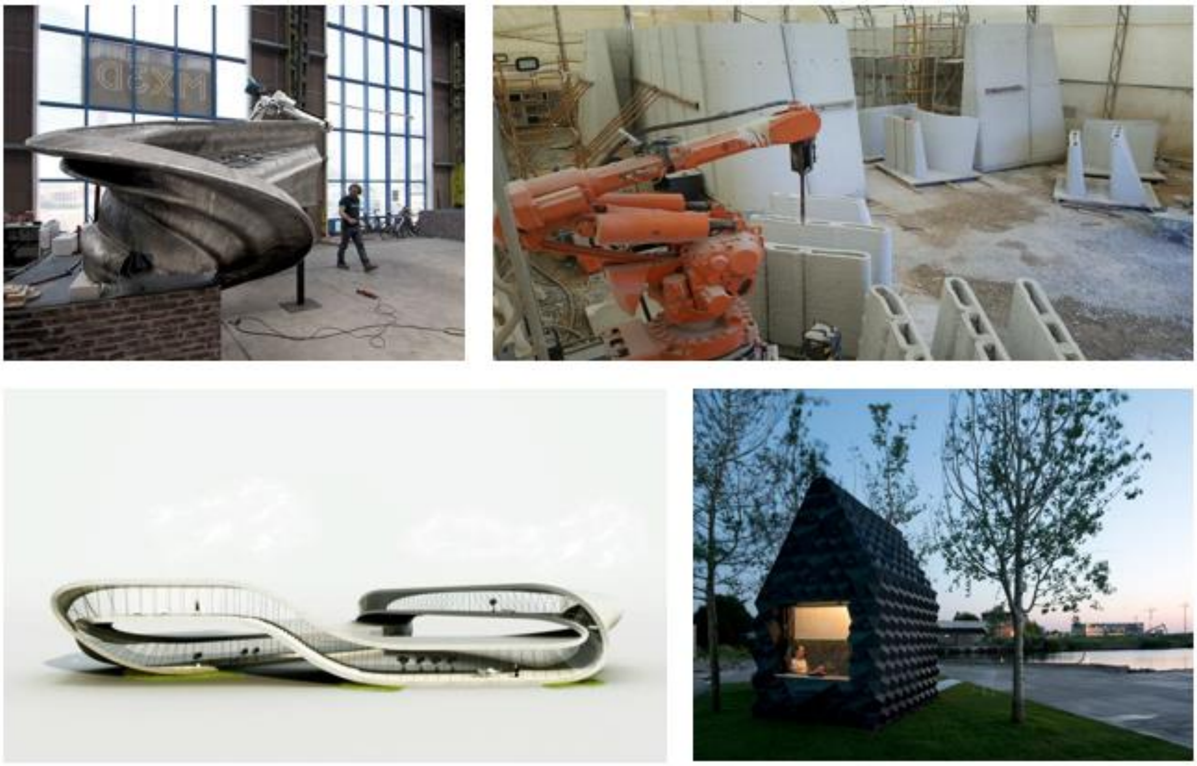


FIGURE 12 MX3D BRIDGE (STEEL) (LAARMAN, 2017), R&DRONE LABORATORY (CONCRETE) (SAUNDERS, 2017), LANDSCAPE HOUSE (STONE) (TESS, 2016) 3D PRINTED MICRO HOME (PLASTIC) (FREARSON, 2016)

Printed elements

No projects exist yet where a full building has been printed by 3D printing only. Rather, specific elements within the overall project are printed. To be able to distinguish the type of components that is printed without making it project specific, the 6S model is used. This is a model developed by Stuart Brand in the 1990's and refers to the different layers that a building consists of: stuff, space, services, skin, structure, and site. (Arup Foresight, 2016) Printed elements that were identified in projects were stuff, space, structure and skin. *Stuff* refers to the elements inside the building that complete the layout, like furniture. *Space* refers to the internal walls that divide the spaces within the building. *Structure* refers to the load bearing elements within the building. *Skin* refers to the façade and exterior. Though some elements fall into multiple categories, it is a useful distinction to make when assessing the later impact on project governance. Examples in these categories can be found in figure 13.

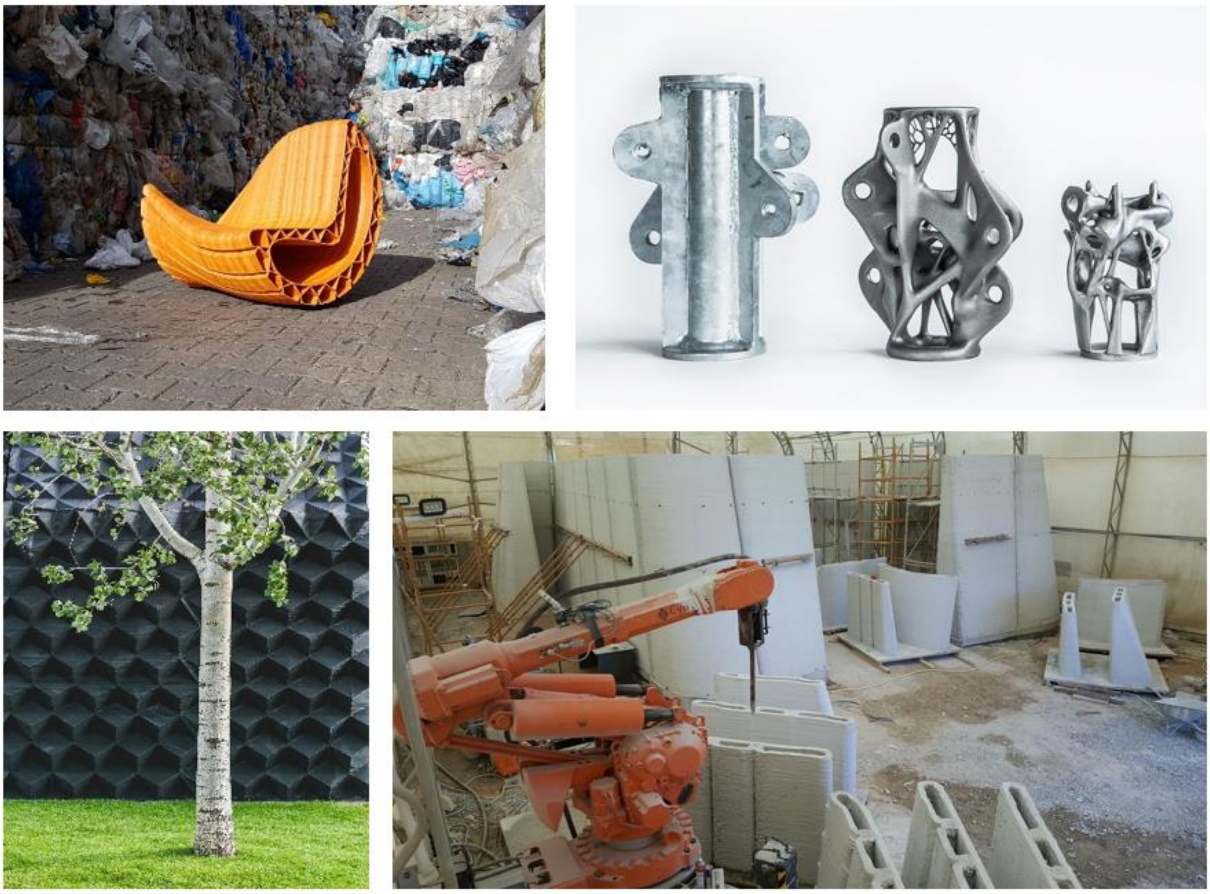


FIGURE 13 3D-PRINTING IN THE CIRCULAR CITY" (STUFF) (PICTURE OBTAINED FROM INTERVIEWEE), OPTIMIZED STEEL NODES (STRUCTURE) (GALJAARD, HOFMAN, PERRY, ET AL., 2015), 3D PRINTED FACADES DUS (SKIN) (DEMEEUW, 2017), R&DRONE LABORATORY (SPACE) (SAUNDERS, 2017)

Location of production
3D printed elements can be manufactured both on site and off site. On site has the advantage that logistical complexity (moving equipment from and away from the site) can be reduced, but adds the challenge that the printed elements are exposed to weather conditions. At the moment off site printing is the most used location for production. Several projects show however, that onsite printing is also a possibility (see figure 14).

FIGURE 14 MX3D BRIDGE (OFF SITE) (LAARMAN, 2017) R&DRONE LABORATORY (ON SITE) (SAUNDERS, 2017)

Printing Style
Two printing styles can be observed in the cases: "inside the box" and "outside the box". Traditionally, the size of printed elements was limited by the dimensions of the printer in which it was made. Printing large components therefore initially required larger printers. In this research, this principle is referred to as "inside the box" printing.

A new development is printing "outside the box", which refers to printing systems that can fabricate components with dimensions larger than themselves. Often industrial robots are used for this purpose. This makes on site printing more feasible, as smaller printing systems can be more easily shipped to site and mobilization time is reduced. Figure 15 provides examples of both printing styles.

FIGURE 15 APIS COR HOUSE (OUTSIDE THE BOX) (CORBOY, 2017), WASP PROJECT ITALY (INSIDE THE BOX) (WANG, 2016)

Employed Technology
Printing can be done in a wide variety of technologies. The technologies observed during the case inventarisation are FDM for concrete and plastics, SLS for steel, and Binder Jetting for stone. New technologies are still being developed, like a new technology which increases the speed of the 3D printing of metal by 100 times. (Rotman, 2017) Because this research has a managerial focus rather than a technical one, the technologies are not actively described in this research. For more details, the reader is referred to contour crafting (FDM), Enrico Dini (binder jetting), and MX3D (SLS).

Relations between characteristics
It should be noted that these characteristics are not independent from each other. For example, whether to produce off or on site is likely to depend on the scale of the printed elements. Product scale elements like joints can be shipped to site relatively easy, where for large building scale components this is not the case. The main point is that there is a wide variety of potential applications area's and methods for 3D printing. Two scenarios for which governance structures will be designed are presented in paragraph 4.6.5.

4.5 Challenges

Besides the frequently mentioned opportunities 3D printing presents, there are a large number of challenges that have to be resolved before wide-scale application in the construction industry becomes feasible. These challenges were identified through literature review, exploratory interviews and a workshop from XtreeE, a manufacturer specialized in 3D printing concrete. The challenges can be categorized in technical, cultural, financial, legal, and managerial.

Technical
Technical limitations include the limited capabilities of robotics and materials, which impose limitations on the degree of design freedom that can be achieved (like inclination angle and size). Integrating installations and reinforcement into walls has also not yet been realized (IDEA Consult, AIT, VTT, CECIMO, 2016) Furthermore, size, volume, printing speed and cost are not yet satisfactory compared to (specialized) traditional technologies. (IDEA Consult, AIT, VTT, CECIMO, 2016) On-site production introduces additional challenges like exposure to heat, humidity and material preparation[3]

[3]Based on a 3D printing workshop by XtreeE

Cultural
Digital fabrication introduces the possibility of a new paradigm of design and production, which is vastly different from the conventional way of production. The supply chain and its involved actors like clients, contractors, architects and suppliers are all accustomed to the standard way of doing things and all existing processes and business models are shaped around it. A report from the European commission identified the conservative nature of the construction industry and its reluctance to innovate as a key limitation for the adoption of 3D printing. (IDEA Consult, AIT, VTT, CECIMO, 2016) An additional challenge in this category is that the existing actors do not yet possess the expertise and skills required to fabricate digitally. (IDEA Consult, AIT, VTT, CECIMO, 2016) The Bartlett school of architecture is launching a number of educational programs that deal with this issue. (Menges, Sheili, Glynn, & Skavara, 2017)

Financial
Most activities currently revolve around research and the creation of artefacts. Because construction is a project-based activity however, the ratio of value to cost of using 3D printing in real projects should be higher than using traditional methods for it to be applied on a large scale. Mass customization and design freedom are frequently mentioned advantages of digital fabrication, but a strong demand for it from the market does not yet seem to be present. As a keynote speaker from the FABRICATE conference stated: *"Over the last few years the technology has developed more rapidly than the demand for it"*[4] This is an indicator that the value to cost ratio of 3D printing is not yet competitive with traditional manufacturing methods. Perhaps this is due to the fact that the technology is still at a low level of maturity and traditional methods still allow for more customization then digital fabrication does. Another possibility is that the possibilities have not yet been demonstrated sufficiently. As Steve Jobs well-known quote stated: "*A lot of times, people don't know what they want until you show it to them.",* referring to the introduction of the IPhone which created a very large demand by introducing it in the market without a clear predefined demand for it from customers. According to Wu et all, the success of 3D Printing in the construction industry will depend on two aspects: the demand for the additional level of customization it offers and the extent to which the conventional production methods are able meet this demand (Labonnote et al., 2016)].

Legal
Buildings have to comply with safety regulations. For 3D printed products, these standards are not yet present. Verification becomes particularly difficult when every part is unique and requires its own verification process. At the moment, this is an additional activity which is not required in a conventional production process. A solution proposed by XtreeE's management director is to verify the manufacturing process instead of its realized products. Another solution is to cast the components contour and then cast the concrete (with known properties) in it.[5] Structural safety should not only be ascertained upon delivery of the printed component, but also over its entire lifetime. Because construction projects have long lifecycles and knowledge on long term performance of 3D printed components is not yet present, this constitutes an additional challenge on this domain.

Managerial
Realizing the full benefits of 3D printing requires a holistic design process, in which the production process should be taken into account at the start of the project. (Labonnote et al., 2016) According to Bos et all it is important to recognize that in 3D printing there is a strong interdependency between the material, design, process and the final product. (Bos et al., 2016) When looking at the construction industry however, it can be observed that it is extremely fragmented (Chartered Institute Of Building, 2014), both horizontally (across different phases) and vertically (within the phases). In this organizationally fragmented environment it can be a challenge to facilitate this holistic design process. Though current BIM platforms and integrated contracts like D&B, DBFMO are increasingly applied to facilitate more integration, the most commonly used method of procurement is still traditional (according to an RICS survey in 2007) (Chartered Institute Of Building, 2016) in which the design and construction is split up in separate contracts and performed by different organizations.

[4] Heard from Arup attendee at FABRICATE 2017 conference
[5] Based on a 3D printing workshop by XtreeE

4.6 Future development of 3D Printing

Though 3D printing is currently at a low level of maturity, it is developing rapidly. As Bos et all point out, current developments are going so fast that any attempt to make a complete overview of a state of the art is out of date as soon as it is published. (Bos et al., 2016) To make the designed governance structures, it is important to gain an understanding of how 3D printing is expected to develop in the future, particularly for the second scenario described in 4.6.5.

To provide starting points for this analysis, this paragraph presents insights gained from desk research, exploratory interviews and the attendance of the 3D printing conference Amsterdam (see appendix B for the obtained insights) on how 3D printing is expected to develop in the future. Expected growth of the market is first discussed to ground the statement that 3D printing will be increasingly applied in the future (4.6.1). Literature on how new (disruptive) innovations are generally adopted in new markets is then presented (4.6.2). This provides insight in how different 3D printing applications are expected to be adopted in the market over time. A process improvement framework is presented (4.6.3), which provides insight in how the processes of applying 3D printed components in construction projects are expected to develop. It also serves as a measurement tool to measure how mature the processes in the case studies are. Current technological developments and trends are then discussed which strengthen the potential of 3D printing, after which general conclusions are drawn (4.6.4). Finally, the wide variety of projects in which 3D printing is applied are categorized in two main scenario's for which governance structures will be designed (4.6.5)

4.6.1 Expected Market Growth

A market growth analysis and forecast done by EY shows that 3D printing will continue to see growth in the future, which EY estimates at 25% towards a market volume of over 10 billion dollars by 2019. (EY, 2016) Their forecast is described in figure 16.

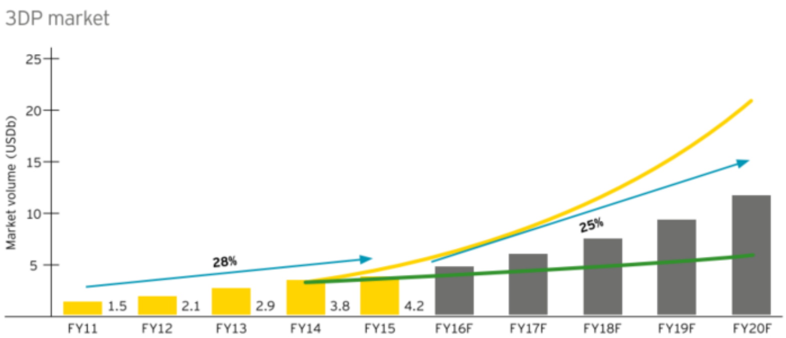


FIGURE 16 GROWTH 3D PRINTING MARKET (EY, 2016)

This forecast was done before the 1,4 billion dollar acquisitions by General Electric (Clough et al., 2016) and the entrance of HP in the market (see appendix B), which means the forecast is likely to be conservative. It can be concluded from this that 3D printing is expected to develop further and mature over time.

4.6.2 Adoption cycle for disruptive innovations

This subparagraph describes the way in which disruptive innovations are generally adopted in new markets. This is based on Moore's book Crossing the Chasm (Moore, 2014), which is an expansion of Roger's Diffusion of Innovation (E. M. Rogers, 2010).

Rogers created a model to describe how an innovation is adopted in a new market. (E. M. Rogers, 2010) It shows how in the initial phases there is little adoption, and describes how the development over time follows an S-curve (see figure 17)

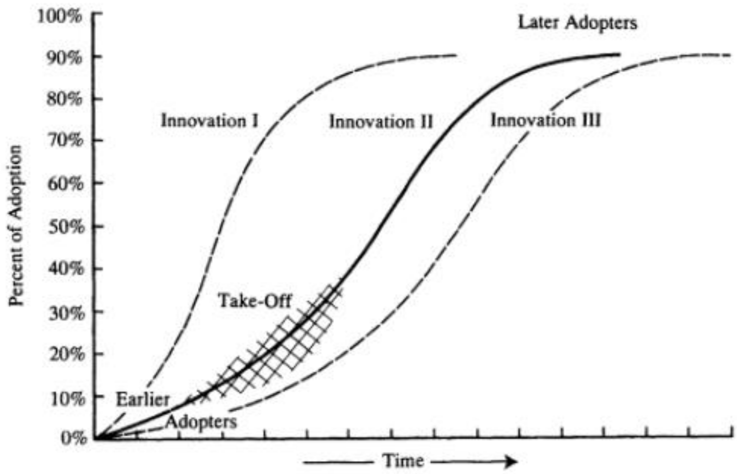


FIGURE 17 THE PROCESS BY WHICH AN INNOVATION IS ADOPTED IN A NEW MARKET (E. M. ROGERS, 2010)

Moore expanded on Roger's model in his book Crossing the Chasm, which describes the adoption process for high-tech disruptive innovations. A disruptive technology is one that requires substantial behavioral change from the customer. (Moore, 2014) 3D printing will indeed require a behavioral change of (multiple) project stakeholders. Therefore, this framework is suitable for assessing the future development of 3D printing.

The expansion of Moore on the original model, is that technologies are adopted in stages. Each stage is represented by a specific customer segment with particular demographics and needs. Ideally, the transitioning from one stage to the next is a smooth process. For disruptive innovations however, challenges exist in transitioning from one stage to the next. This is particularly true for the transitioning from the early market (innovators and early adopters) to the mainstream market (early majority, late majority). These challenges are considered as gaps or "chasms" between the stages, and are described in figure 17. Since 3D printing is currently at a research and prototyping stage (IDEA Consult, AIT, VTT, CECIMO, 2016), the customer segments innovators, early adopters and early majority and their transition are briefly discussed.

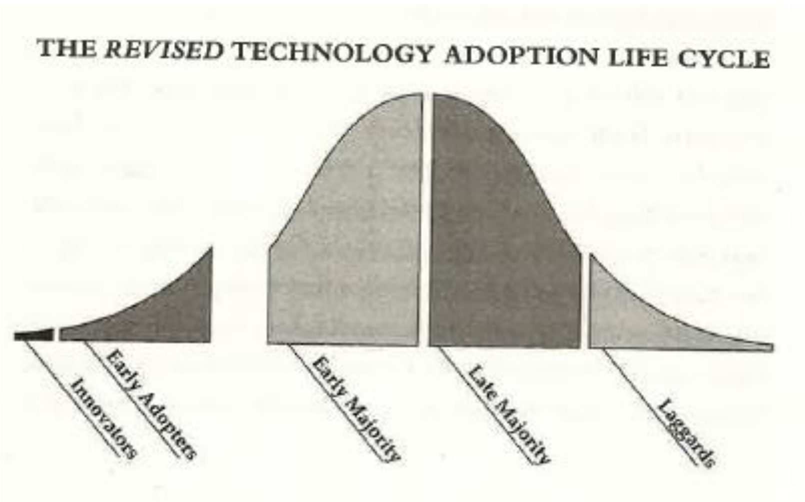


FIGURE 18 STAGES IN WHICH A DISRUPTIVE INNOVATION IS ADOPTED

Innovators

Innovators view technology as having an intrinsic value. They want to have the newest products and do not necessarily care whether it has bugs in it or not. They are also the least price sensitive for new innovations.

Early adopters (Visionaries)
Visionaries aim to match an emerging technology with a strategic opportunity. They take on a high risk (high reward) project to realize this opportunity. Rather than looking at innovation as a means for incremental improvements, they look for fundamental breakthroughs. Most often these are large organizations that are leaders in their industry that take large risks to implement a new innovation.

Early majority (Pragmatists)
Pragmatists adopt a technology because it offers an improvement to their existing processes. They preferably buy well referenced products that are proven to work from established vendors.

Transitioning from visionaries to pragmatists: the chasm
The chasm originates from the fact that the motivation for visionaries and pragmatists to buy the innovative products or services are different. Visionaries seek fundamental breakthroughs and are oriented towards the future possibilities. Pragmatists are concerned with business cases and incremental improvements. They will only adopt a technology once it is well referenced (by other pragmatists), has underlying support systems, and offers an improvement to their existing processes at low risk. This makes this transition very hard to make, because these requirements are not met in the early stages of development of a market. One pragmatist has to go "first". The recommendations Moore makes for moving past this challenging transitioning phase revolve around two main insights:

- Start with a niche market in which you become the market leader, then slowly expand towards other markets.
- You must fully address all customer needs in this niche market, by delivering a holistic product or service.

4.6.3 Capability maturity model

The capability maturity model is a process improvement framework originating from the software industry. (Paulk, 1993) It describes several levels of maturity of capabilities, which are described in figure 19.

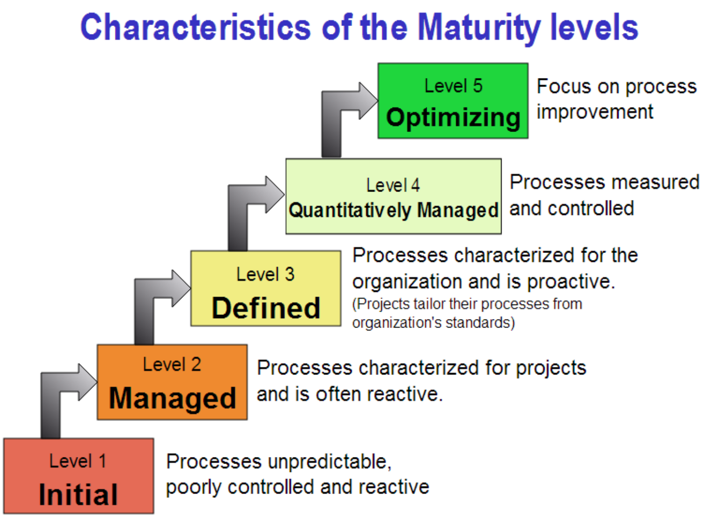


FIGURE 19 CAPABILITY MATURITY LEVELS (BASED ON (PAULK, 1993))

This model provides an opportunity to measure the maturity of processes, which is of value when assessing the maturity of the process of applying 3D printing in a construction project. New processes often start at level 1, and move towards level 5 as they mature.

4.6.4 Current developments

3D printing technology is developing rapidly. Based on desk research, exploratory interviews and presentations during the 3D printing conference in Amsterdam and the Imprimer le monde conference (see appendix A and B), this paragraph lists the most important developments in the market and for 3D printing technology. It also presents supporting digital technologies and trends which strengthen the potential of 3D printing and an overall conclusion to what these mean for the adoption process of 3D printing.

Market developments

The early 3D printing market was dominated by four players (EOS, 3D Systems, Stratasys, Materialise) (EY, 2016). In 2017, two large visionary organizations entered the 3D printing market: HP and General Eletric. The motivation a lead developer at HP gave for investing in the technology is the expected transition from 3D printing small scale prototypes and tools towards the manufacturing of end-products, which constitutes a very large market (see appendix B).

In the construction industry, the technology is primarily applied in research projects and artefacts, though currently the first functional projects in which it is applied are emerging. A selection of these projects is investigated in this research.

Technological developments

Technological developments can be observed in robotics, materials, and software. Robotic 3D printing systems can 3D print increasingly large objects, which increases the range of components in construction projects that could be 3D printed. Examples are Voxeljet's large scale (freeform) sand printing systems (in which molten metal is casted) (Voxeljet, 2017), a recently approved prototype for a shipping propeller (DAMEN, 2017), and Apis Cor's manufacturing systems to 3D print the majority of the building. (Corboy, 2017) Where robotic systems were originally static and only used in controlled environments, more mobile systems are emerging in which industrial robots are mounted with 3D printing technology to print components on site. On site printing combined with product integration would greatly simplify construction logistics as less elements have to be manufactured and transported. Originally the materials in which 3D printing was possible were primarily plastics. More recently 3D printed applications can be observed in steel and concrete. The possibility of printing in construction materials increases the range of construction components that can be 3D printed. A lead developer within HP stated that though their original focus is on printing plastics, expansion towards other materials is likely in the future (see appendix B). State of the art printing systems most often only print in one material, though the first systems are introduced that can print multiple materials in the same component. Additionally, new materials are being designed which satisfy multiple performance requirements that normally have to be fulfilled by using different types of materials. An example is the Geocement co-developed by Renca and Apis Cor (Apis Cor, 2017) These developments further strengthen the product integration possibilities. In terms of software, design software is being developed that helps designers to utilize the freeform possibilities of 3D printing and in turn increases the additional value freeform components could provide. Wits stated during the 3D Printing conference in Amsterdam that *"where normally manufacturing is running behind on designers, it is now the other way around"* (see appendix B), referring to the fact that the majority of traditional design software programs are not capable of utilizing the freeform shapes that can be manufactured by 3D printing. An examples of a program that can accomplish this is Autodesk's generative design software (Autodesk, 2017a). It uses artificial intelligence and scripted algorithms that aid in optimizing an object for a specific function.

Supporting digital technologies

Several digital technologies strengthen the potential of 3D printing. Technologies include internet of things, augmented/virtual reality, and artificial intelligence. Internet of Things can contribute in the development of certified manufacturing process. Data can be collected from cheaply placed sensors, which verify whether the manufacturing process is producing the object as virtually designed. The development of a certified production process would eliminate the need to physically test 3D printed products after they are finished. Internet of Things can also play a role in measuring the performance of a 3D printed object after it has been installed, since there is little knowledge on long term performance of 3D printed objects and construction projects are characterized by long lifecycles. Augmented/Virtual Reality can contribute in facilitating the required holistic design process by enabling easier and more direct communication between the fragmented disciplines when they are at different geographical locations. (Autodesk, 2017b) Finally, Artificial Intelligence can be used to help designers utilize the freeform opportunities of 3D printing.

Enabling trends in the construction industry
Besides developments in digital technologies, several trends can be observed in the construction industry which enable the adoption of 3D printing. These trends include digital design (BIM), digital fabrication, sustainability, and integration of the project value chain (removal of intermediaries). Applying BIM aims to make a complete virtual model of a project before it is being constructed. BIM is already adopted on a large scale in the UK, where it is a governmentally issued requirement for construction projects. BIM shows a strong coupling to 3D printing in the design phase, since they both require a complete virtual model to be made before actual construction is started. This means that lessons learned from BIM can be applied when designing (large scale) 3D printed components. The key difference however is in the production phase. With BIM, the virtual model is still manufactured and assembled using traditional manufacturing methods, where in the case of 3D printing the objects are manufactured digitally. Digital fabrication is the wider category in which 3D printing can be placed, and also includes computer controlled subtractive and casting methods. Combining 3D printing with these methods allows to make automated digital manufacturing systems, increasing the range of components that can be printed and improving quality and speed. (examples can be found in paragraph 4.1). Sustainability is a topic that is becoming increasingly important in the construction industry, and could be an incentive for a client to apply 3D printing. Developments on this domain can be observed in which waste materials are re-used by transforming them into new printing materials. Re-using materials is already possible for plastics. (DeMeeuw, 2017) For concrete, concepts exist using hydro jetting (Haciomeroglu, 2013), but these have not seen adoption in the mainstream market. The other reason 3D printing could be more sustainable is the simplification of site logistics (due to product integration), little generated waste and reduction of material usage (and CO2 emissions). The final most important trend that facilitates the holistic design process 3D printing requires is the integration of the project value chain that can Rogers lists the disintermediation of supply chains as a global trend (D. Rogers, 2016). This trend reveals itself in multiple developments in the construction industry. Firstly, customers are increasingly engaged to design their own products (Materialise), rooms (IKEA), and more recently houses (BAM[6] and BPD (BPD, 2017). Integrated contracts like D&B and DBFMO are being increasingly adopted, and contractors increasingly buy required expertise so they can do the full design and construction in house[7]. The integration of the project value chain is further enabled when design activities can be automated. Within Arup design programs exist where input parameters are inserted in a model and a complete output of all required drawings and specifications can be done in very short timespans. (Fysion & Clipsom, 2017)

Conclusion
3D printing has strong couplings to other digital technologies and trends in the construction industry, which enable its adoption. These trends are expected to continue, regardless of how 3D printing will develop in the future. This increases the likelihood that 3D printing will be adopted on a large scale in the future.

The second conclusion that can be drawn is that both the application of 3D printing in construction projects and the development of 3D printing technology require close interdisciplinary collaboration between different organizations and industries. An innovation model from literature that is suitable for these characteristics are so called open innovation models (Du Preez, Louw, Preez, & Louw, 2014). Open

[6] Discussed during a validation interview with Jonker (BAM Tender Manager)
[7] As stated by the director of the Arup AMS office

innovation models are opposed to traditional approaches to innovation, in which organizations develop new innovations within the boundaries of their own organization.

4.6.5 Future development scenario's

Paragraph 4.4 highlighted the wide variety of application area's for 3D printing in construction projects. These can be classified in two main scenarios:

1) A construction project in which a number of 3D printed components is applied
2) A building in which the majority is 3D printed

3D Printed components
3D printing is applied for specific components in specific types of projects (that require a freeform in their design for example). Due to their specific nature however, only a small number of components will be printed per project, so that the traditional governance of a construction project remains dominant.

This scenario captures the pragmatist perspective, who view 3D printing as a means to achieve a better component, at a lower cost. The threshold for adoption is relatively low, since it requires relatively little behavioral change for the overall project. The type of element which will be adopted in construction projects first is uncertain. Developments can be seen for ornaments (Great Pagoda Project in paragraph 6.5), facades (Strauß & Knaack, 2016), structural joints (Galjaard, Hofman, Perry, et al., 2015), walls (Bos et al., 2016), and columns (XTreeE, 2017).

3D Printing the majority of a building
3D printing is the main production technology for a large percentage of the buildings components. The building is mostly digitally manufactured and assembled on site, and supported by off site prefabricated elements produced by other (digital) fabrication g methods. A small number of operators oversees site operations, though the process is largely automated.

This scenario captures the innovators and visionaries perspective on 3D printing, and follows the suggestion of FABRICATE 2017 that "*Industry 4.0 will have - indeed, is already having - a profound impact on the way the future built environment is conceived, designed and materialized*"(Menges et al., 2017)

For both scenario's, governance structures will be designed. The governance structure for a current construction project in which 3D printed components are applied is discussed in chapter 8. An explorative governance structure for a future scenario in which the majority of a building is 3D printed is presented in chapter 9.

5 Project Governance

With the state of the art of 3D printing analyzed, this chapter presents the operationalization of project governance that will be maintained throughout this research and presents literature on the governance that is expected in the case studies. Project governance is defined, distinguished from project management and broken down into several elements in paragraph 5.1. These elements can be combined in different ways for different purposes. Three domains that were found in the case studies are the governance of traditional construction projects, product design and innovation. Literature on the governance of these domains is presented in paragraph 5.2 to 5.4. A high level overview of the governance elements of each domain is then provided in paragraph 5.5.

5.1 Operationalization

In this paragraph, project governance is fully operationalized by breaking it down into its elements phases activities, roles and responsibilities (5.1.2) and broken down into project and product level (5.1.3). Before making this operationalization, the concept is defined.

5.1.1 Definition

Put simply, project governance entails "*how to run a project*"(Klok, 2015). When looking at literature, it can be observed that the original Latin term from which governance is derived, means 'to steer' (Samset & Volden, 2016) This can be on a national (government), organizational, or project level. When related to projects, it refers to "*the processes, systems, and regulations that the financing party must have in place to ensure that projects are successful*" (Samset & Volden, 2016) Project governance distinguishes itself from project management by providing the frameworks within which the project should be managed, where project management is concerned with execution of the project within the boundaries of these frameworks. (Müller & Lecoeuvre, 2014) (Biesenthal & Wilden, 2014) Project governance can therefore be understood as the collection of processes and methods to successfully steer projects. One of these methods are so called project governance structures, which *"outlines roles and responsibilities for everyone in the project"* (Chartered Institute Of Building, 2014)

A tool that can be used in defining responsibilities in multi-actor projects is a responsibility assignment matrix (RAM), which provides project stakeholders with insight in the responsibilities for project activities. (Project Management Institute (PMI), 2013) An example of a RAM that is often used is the RACI model. (Chartered Institute Of Building, 2014; Project Management Institute (PMI), 2013) (see figure 20).

RACI Chart	**Person**				
Activity	Ann	Ben	Carlos	Dina	Ed
Create charter	A	R	I	I	I
Collect requirements	I	A	R	C	C
Submit change request	I	A	R	R	C
Develop test plan	A	C	I	I	R

R = Responsible A = Accountable C = Consult I = Inform

FIGURE 20 RACI MATRIX (PROJECT MANAGEMENT INSTITUTE (PMI), 2013)

A closely related alternative that applies the same principle is the RASCI method. The letters RASCI stand for:

- **R**esponsible, the actor responsible for the task and who is doing the work.
- **A**ccountable, the actor who is ultimately answerable to the completion of the task, and who often receives the deliverable from the one who is responsible.
- **S**upporting, the actor that supports in completion of the task (doing actual work)
- **C**onsulted, the actor who is consulted (two-way communication), these are often experts.
- **I**nformed, the actor who is informed on progress and on completion of the deliverable (one-way communication)

Creating a RASCI matrix requires the identification of the following elements:

- The work that has to be done (phases, activities)
- Who is involved in the project (roles, organizations)
- Allocation of responsibility (how responsibility for the work to be done is allocated to those involved in the project)

These elements are further operationalized and defined in the next paragraph.

5.1.2 Project governance elements

Based on the literature in the previous paragraph, a further operationalization of project governance is made by breaking it down into elements that can be measured in projects and defining these elements. Project governance in this research includes the following four elements:

- Activities
- Phases
- Organizations and roles
- Responsibilities

Activities
Activities imply specific actions that have to be done to realize a part of a project.

Phases
Phases are groups of related activities that have to be done in a coherent manner in order to create a deliverable or milestone, that is a part of the overall project.

Organizations and roles
The Cambridge dictionary defines a role as *"the position or purpose that someone or something has in a situation, organization, society, or relationship"* (*Cambridge Dictionary*, 2017) In a project, it is therefore understood as the position or purpose that someone has in a project. Project roles are often accompanied with certain rights and responsibilities and show different degrees of involvement in the phases of a project. Examples of common roles for a construction project are the client, project manager, architect, engineer, contractor and supplier.

Organizations are companies that can potentially take on these roles and their related responsibilities. Though often companies specialize in certain project roles, their role can differ from project to project. For example, project management services can be the responsibility of an architectural firm, engineering firm or a specialized project management consultancy.

Responsibilities
Though roles often imply certain related responsibilities, the exact responsibilities depend on the contract that is used. Responsibilities can exist for an individual activity, a phase, or a physical element.

5.2 Governance of traditional construction projects

This paragraph presents literature on the governance elements of a traditional construction project, by presenting its phases (5.2.1), activities (5.2.2), organizations and roles (5.2.3) and responsibilities (5.2.4).

5.2.1 Lifecycle phases

There is a wide variety of frameworks available that present the different phases for a construction project, as can be observed in figure 21.

Code of Practice for Project Management	Royal Institute of British Architects (RIBA) Plan of Work 2013	BIM Digital Plan of Work 2013	BS 6079-1:2010	ISO 21500:2012
1 Inception	0 Strategic definition	1 Strategy	1 Conception	1 Initiating
2 Feasibility	1 Preparation and brief	2 Brief	2 Feasibility	2 Planning
3 Strategy	2 Concept design	3 Concept 4 Definition		
4 Pre-construction	3 Developed design 4 Technical design	5 Design	3 Realisation	3 Implementing
5 Construction 6 Testing and commissioning	5 Construction	6 Build & commission		
7 Completion, handover and operation	6 Handover & close out	7 Handover & close out	4 Operation	4 Controlling
8 Post-completion review and in use	7 In use	8 Operation & end of life	5 Termination	5 Closing

FIGURE 21 PROJECT LIFECYCLE PHASES BY SEVERAL INSTITUTIONS (CHARTERED INSTITUTE OF BUILDING, 2014)

For this research, the Dutch framework STB 2009 is chosen to lists the lifecycle phases of a standard Dutch project. The motivation for this decision is twofold: it has multiple levels of detail (both on phases, activity themes and activities) and it is likely to be more familiar to the (mostly Dutch) interviewees.

The phases of the STB 2009 are somewhat different from international frameworks in that the design is split up in multiple levels of specification, like the conceptual design (SO), Preliminary design (VO), Definitive design (DO), Technical design (TO), and even an execution design (UO). The relevant project phases are presented in figure 22.

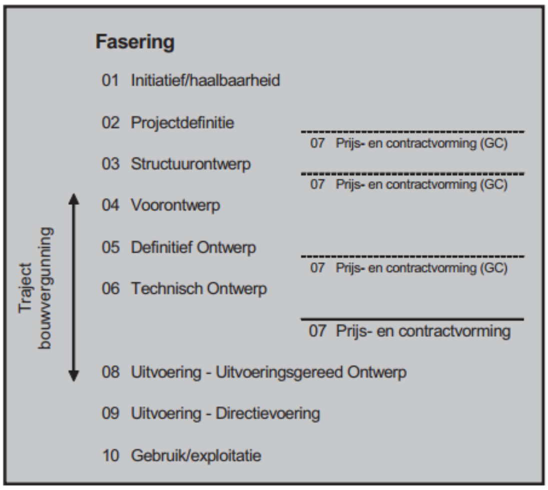


FIGURE 22 PROJECT PHASES STB 2009 (BNA ET AL., 2009)

5.2.2 Activities

The STB-DNR 2009 lists over 2000 activities that are required to "*come to a responsible design and execution of a project*"(BNA et al., 2009). These activities are subdivided over the phases and are grouped into several activity themes. These themes are grouped in the categories client, design and project management themes. A detailed list of these themes are presented in figure 23. For a more detailed description of the activities, the reader is referred to the STB-DNR 2009 (BNA et al., 2009)

STB Thema's

Opdrachtgeversthema's	Ontwerpthema's	Projectmanagementthema's
01 Opdrachtgeving	04 Architectuur/bouwkunde	12 Geld
02 Contracten	05 Interieur	13 Organisatie/procesintegratie
03 Programma van Eisen	06 Landschap	14 Tijd
	07 Bouwfysica en akoestiek	15 Informatie en communicatie
	08 Constructie	16 Kwaliteitszorg en risico's
	09 Installaties	
	10 Geotechniek	
	11 Ontwerpintegratie	17 Vergunningen
18 Geïntegreerde contracten		

FIGURE 23 STB ACTIVITY THEMES (BNA et al., 2009)

5.2.3 Organizations and roles

Though the exact project team structure varies widely and depends on the unique characteristics of a project, the roles in figure 24 are described as "typical" by the CIOB framework. (Chartered Institute Of Building, 2014) The main roles are that of the client, project manager, architect, engineer, contractor, subcontractor and specialist suppliers.

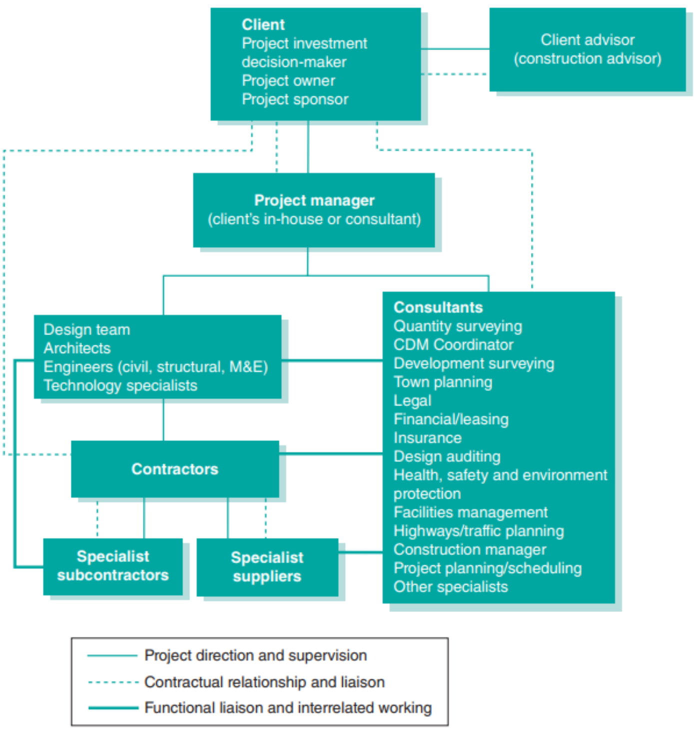


FIGURE 24 TYPICAL PROJECT TEAM STRUCTURE (Chartered Institute Of Building, 2014)

Client
The client is the project owner and financier. He is involved in all phases of the project. Organizations that fulfill this role can be both public and private.

Project Manager
The project manager is the client's representative to realize his project within budget and schedule, at a sufficient quality. He is involved in all project phases, and can add the most value during the initial (strategic) project phases. Organizations that fulfil this role differ from project to project. Examples can be observed from engineering firms, architectural firms, contractors, or consultancy's specializing in project management services.

Architect
The architect is the overall designer of the project. He is involved most during the design phase and can also have a role during the construction phase. Organizations that fulfil this role are often architectural firms.

Engineer
The engineer is the technical designer of the project, providing technical expertise to the architects design. This can be on several domains (engineering disciplines). The engineer is involved most during the design phase and can also have a role in the construction phase. Organizations that fulfil this role are often engineering firms.

Contractor
The contractor builds the project as designed by the architect and engineer. He has a dominant position in the construction phase, and his expertise can be sought in the design phase. Organizations that fulfil this role have the same name: contractors.

Subcontractor
The subcontractor builds a part of the project as designed by the architect and engineer. As projects are larger, contractors outsource a part of the work to subcontractors. They are involved in the construction phase (subordinate to the contractor), and their expertise is sometimes sought in the design phase. Organizations that fulfil this role are contractors. Whether an organization is a contractor or subcontractor depends on who is accountable for the overall delivery in an individual project, often driven by the organization's size (larger organizations can take on larger risk).

5.2.4 Responsibilities

The exact responsibilities of the aforementioned roles depend on the project (activities) and type of procurement method that is applied (contracts). This paragraph allocates the responsibility for the client themes discussed in 5.2.2 based on traditionally procured Dutch contracts (DNR + UAC), where responsibility for design and construction are separated.[8] The exact responsibilities can be altered in the contract to meet the unique circumstances in the project. For this research, the following responsibilities are assumed to be standard. With these starting points the responsibilities for every role can be defined as follows:

Client
The client is responsible for the client themes "client interventions", contracts and the program of requirements, which are present throughout all project phases. Client interventions entail making decisions on progress and phase results, and potentially adjusting the starting points or frames in the project (program of requirements). Contracts entail specifying new work packages and contracting them out to third parties. Finally, the client is responsible for creating (and revising) a program of requirements that

[8] An RICS survey in 2007 revealed that the traditional procurement method is still applied most (Chartered Institute Of Building, 2016)).

defines what is to be built. If the client is inexperienced, he is supported by the project manager on these aspects.

Project Manager
The project manager is responsible for steering and governing the project process (organizationally, financially and the schedule). He is also responsible for managing project risks, and ascertaining that the project that is being realized is aligned with the program of requirements. He is responsible for the project management themes: Budget (G), Organization (O), Schedule (T), facilitating communication between the project team (I), and Quality and Risk (K).

Architect
The architect is responsible for the non technical aspects of the design for the overall project. He or she is responsible for the activity themes architecture, interior and landscape. An additional responsibility that is often taken on by the architect is that of design integration, which is about balancing the design input from all involved disciplines and integrating them into the final design.

Engineer
The engineer is responsible for the technical design aspects of the project, which can be on several domains. He or she is responsible for the activity themes building physics and acoustics, structural, installations, and geotechnical.

(Sub)contractor
The contractor is responsible for building the works as designed by the architect and engineer. As projects become larger and in-house capabilities are too small or risk is considered too high, subcontractors are involved to realize part of the works. This always includes a specific scope that is to be realized according to design requirements.

5.3 Governance of 3D printed products

This paragraph presents literature on governance elements of 3D printed products. Lifecycle phases are first discussed on the production process of 3D printed components in the Aerospace industry (5.3.1). Literature on a product design process is then presented (5.3.2), which showed strong similarities to the case studies analyzed in this research (see chapter 6). Organizations and roles in the 3D printing industry are then presented based on a value chain analysis done by EY (5.3.3).

5.3.1 Lifecycle phases 3D printed product

Vieira & Romero-Torres distinguish three phases in creating a 3D printed product: The digital phase, the manufacturing phase, and post processing. (Romero-Torres & Vieira, 2016) This process is highlighted in figure 25.

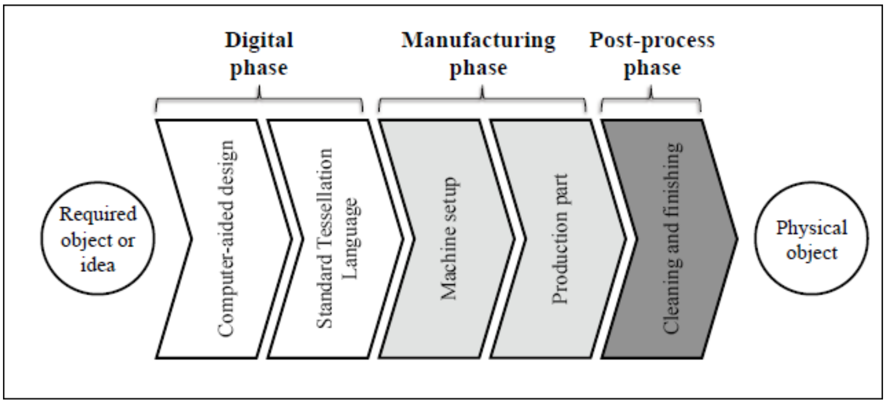


FIGURE 25 PRODUCTION PROCESS FOR A 3D PRINTED COMPONENT (AEROSPACE INDUSTRY) (Romero-Torres & Vieira, 2016)

5.3.2 Product Design

Though the overall lifecycle phases of the model described in figure 26 is clear, the phase "Computer Aided Design" is a very generic term for a complex design process. Models for product design might be suitable to describe this phase in more detail. Many models can be found in literature, which show a general consensus on the methodology. (Roozenburg & Eekels, 1998) In a product design process, a design is increasingly detailed through several phases. An example is the Pahl and Beitz model, which is described in figure 26. Though its representation is structured, in practice the boundaries between these phases are often difficult to define, and iterations between them are common. (Roozenburg & Eekels, 1998) The importance of these iterations are stressed by Cantamessa, who states that: *"The role of iterations in product development is so significant, that the major approaches to its management differ in the way they manage iterations"* (Cantamessa & Francesca, 2016) The organizations within this overall process collaborate closely and resemble a network approach to governance. In the automotive industry for example, the manufacturer and stylists work together during the initial stages of the design process. (Roozenburg & Eekels, 1998) Bringing all relevant disciplines and expertise in at an early stage of the design process has the advantage that the risk of significant changes at a later point in the design process is reduced. This is important, since these the cost of change increases as the design reaches increasing levels of detail. (Cantamessa & Francesca, 2016)

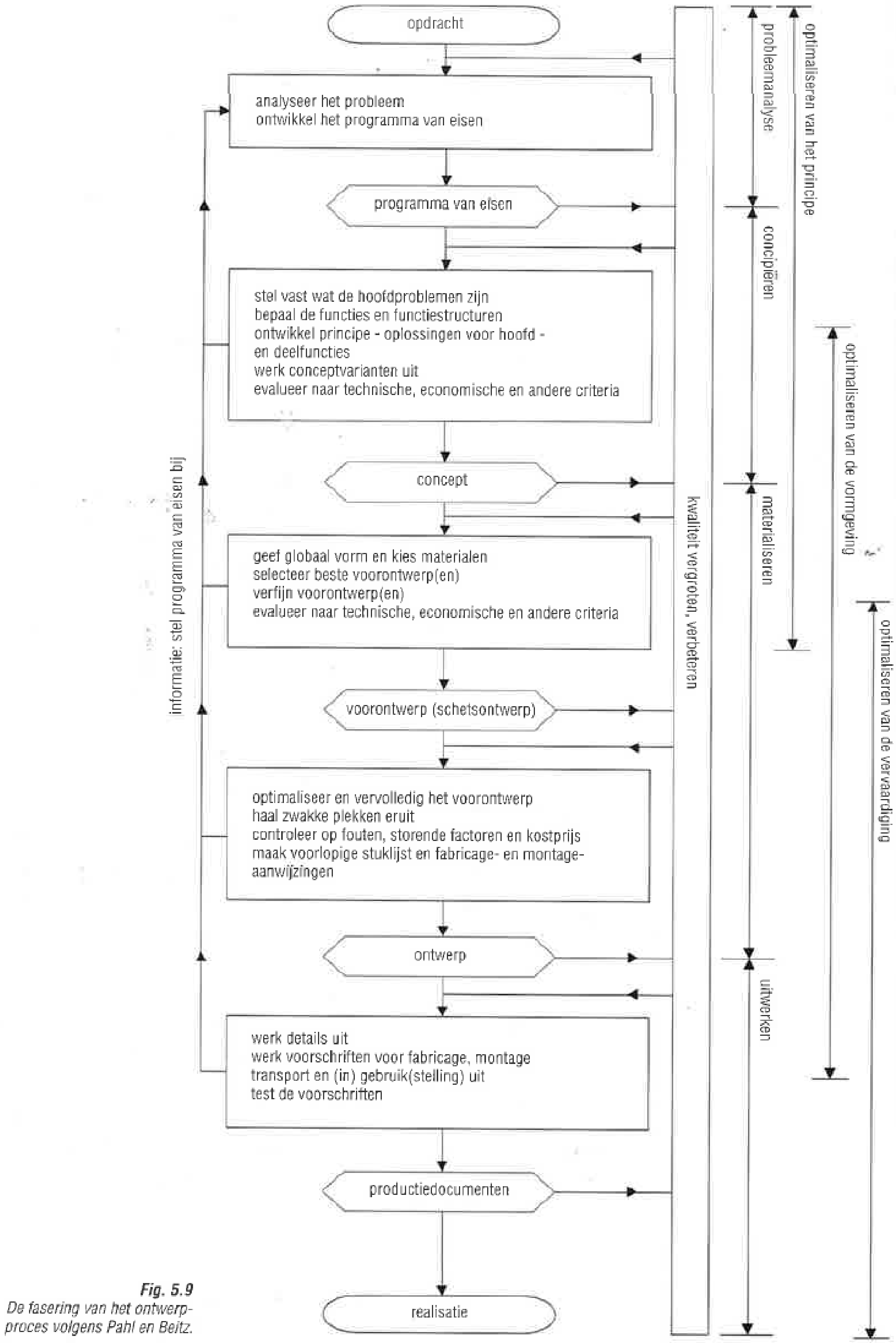


FIGURE 26 PHASING OF THE PRODUCT DESIGN PROCESS (ROOZENBURG & EEKELS, 1998)

5.3.3 Organizations and roles 3D printing industry

This paragraph briefly discusses the 3D printing industry's value chain. The demand and supply side and the involved organizations in the industry are presented in figure 27. A short description of the involved organizations in this value chain is described in this paragraph.

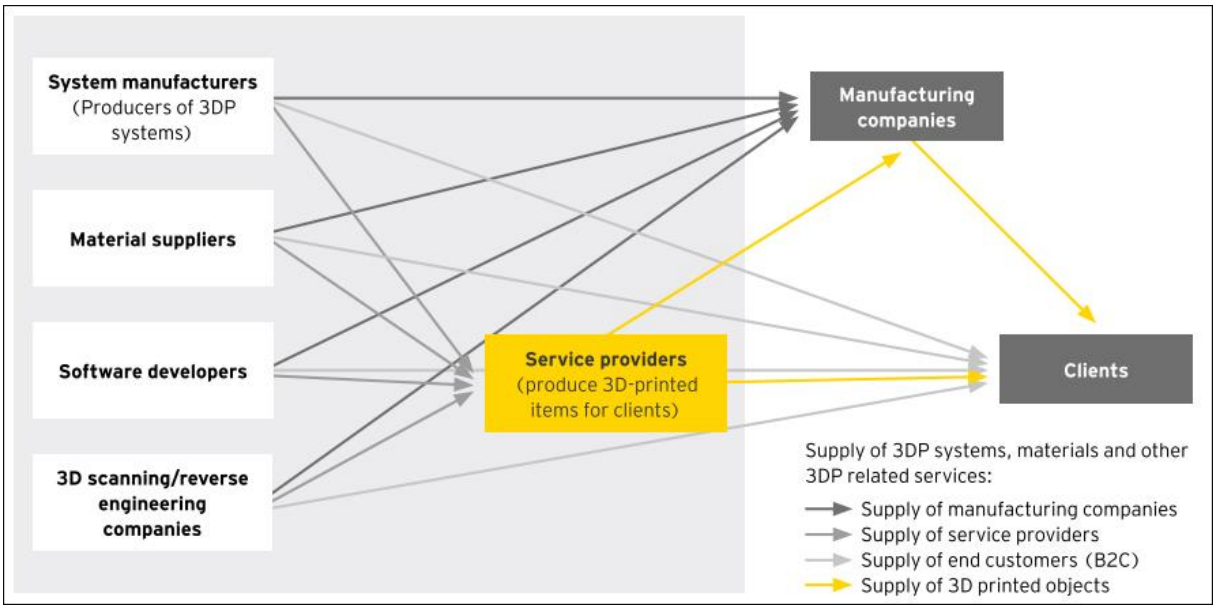


FIGURE 27 VALUE CHAIN 3D PRINTING INDUSTRY (EY, 2016)

System manufacturers

"3D Printing (3DP) systems manufacturers develop systems and (sub-) technologies for the additive manufacturing market. They represent the largest group of players, with the highest supplier market share. The most important systems manufacturers include Stratasys, 3D Systems, EOS, Concept Laser, SLM Solutions, ExOne and Ultimaker. Such companies usually offer related software, materials, engineering, consulting and other services" (EY, 2016)

Material suppliers

"Material suppliers develop and produce materials for 3DP. They usually have knowledge of materials science, heat treatment and sintering processes. Their products range from polymers to metals. While polymer products usually consist of filaments, metal products can be made of powders or wires." (EY, 2016)

Software Developers

"3DP software suppliers are large traditional software companies, alongside some specialist 3DP service providers. Software developers mostly serve systems manufacturers and service providers. Nevertheless, some 3D design and PLM solutions are for the industrial client sector too." (EY, 2016)

3D Scanning/reverse engineering companies.

"The small group of reverse engineering/ 3D scanning companies create 3DP designs from existing structures or products, for example in the architecture, automotive or mechanical engineering industries. The service is used mainly for testing or verification purposes, whether for industrial companies or smaller private-user applications" (EY, 2016)

Service Providers

"3DP service providers represent the group of companies that deliver ready-to-use 3D printed prototypes and products, as well as engineering and 3DP consulting. They belong to the next stage of the value chain, since they are both clients of the previously mentioned suppliers and also supply industrial companies or other clients." (EY, 2016)

5.4 Governance of Innovation

This paragraph defines innovation and presents literature on the way it is governed.

5.4.1 Defining Innovation

The concept of innovation has many definitions and perspectives. A study on a multidisciplinary definition of the concept stated the following definition:

"Innovation is the multi stage process whereby organizations transform ideas into new/improved products, service or processes, in order to advance, compete and differentiate themselves successfully in their marketplace" (Baragheh, Rowley, & Sambrook, 2009)

5.4.2 Governing the innovation process

The governance of innovation was traditionally characterized as a lengthy stage gate process representing the process from having an idea to implementation in the market. Recent literature however, brings new light to this matter. (Cooper, 2015) (D. Rogers, 2016) Stage-gate processes are generally rigid and are not context dependent. The end of each stage is often accompanied with long checklists, reports and financial measurements, which do not directly add value (Cooper, 2015)

New models for managing innovation are therefore emerging, which Cooper (the original developer of the stage-gate process) describes as Triple A systems: adaptive and flexible, agile, and accelerated. (Cooper, 2015) This takes shape in the form of spiral developments, context-based stage definitions and activities, risk-based contingency and flexible criteria for go/kill decisions, an agile process, (Cooper, 2015)

Spiral developments
Spiral developments are characterized by iterative cycles through which the product is more accurately specified. Rather than completely defining the product up front, continuous cycles of build-test-feedback-revise defines the product more exactly as the design process progresses. These cycles can have varying degrees, from 2 to 12 weeks. (Cooper, 2015)

Context based stage definitions and activities
Rather than using the same stage gate model for all of their innovations, companies are increasingly adopting context dependent stage gate models for different type of innovations. (Cooper, 2015) For small technology development projects for example, lighter stage gate models are applied which provide more flexibility and allow for multiple activities to be done at the same time.

Risk-based Contingency
In risk based contingency, the innovation process is described by a series of activities to reduce uncertainties that impact the goals of the overall project. Uncertainties and key assumptions are specified at the start of each phase, and a process is detailed on how to find the relevant information to either reduce the uncertainty or validate the assumptions. (Cooper, 2015) This means that the exact activities are designed and tailor made for the unique project circumstances and status, instead of defining all activities upfront.

Flexible criteria for Go/No-Go decisions
Criteria on which decisions are based for progressing or killing the project are dynamic and less financially oriented. This is not because financial projections are not important, but more that the data underlying these projections is often based on inaccurate information or contains invalid assumptions. (Cooper, 2015)

Agile product development
An emerging model that embodies the principles mentioned above is the Agile approach, which is applied on a large scale for software development. Agile presents an evolutionary development of the design process which is continuously subject to change. The process can be described by a number of short intervals (so called "sprints") in which small teams closely collaborate towards a result which is

continuously validated with the customer or stakeholders. At the end of such an interval, results are presented and based on their results the existing planning and product specifications can be revised. This constitutes a higher number of design iterations when compared to traditional product design models. The management style of this approach is informal, team members are empowered and largely self-organized. (Cantamessa & Francesca, 2016) (Cooper, 2015)

5.5 Overview governance domains

This paragraph describes the governance elements of the different governance domains that were found in the case studies in chapter 6. A high level summary of these domains is presented in figure 28. Each is then briefly described.

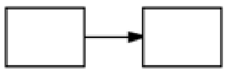
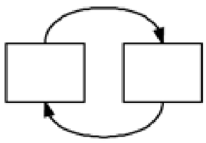
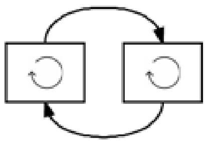
Governance Domains	Phases & Activities	Roles and Responsibilities	Organizations	Characteristics
Construction Project		Defined and rigid	Multiple Organizations Fragmentation	Structured Hierarchy
Product Design		Defined and flexible	In-House Collaboration	Structured Network
Innovation		Defined ad-hoc	In-House Integration	Flexible Network

FIGURE 28 OVERVIEW GOVERNANCE DOMAINS

Construction Project
The governance of traditional construction projects can be characterized by sequential stage gate phases and activities. Each stage gate is coupled to standardized deliverables, which are generally a set of 2D drawings and textual documents. Roles and responsibilities are defined prior to project start, and these generally do not change. There are multiple organizations fulfilling these roles, and there is a clear fragmentation between the design and engineering phase and the construction phase. The relations between the organizations have a hierarchical nature, with the architect generally leading the design phase and the contractor leading the construction phase (supervised by the architect).

Product Design
The governance of product design can be described by a similar stage gate process, though these gates are more flexible than that of a construction project. Iterations between design phases are common and expected, rather than avoided. Roles and responsibilities are defined, but these are more flexible as the project continues. Project actors develop the product in-house, and closely collaborate. The relationships between them therefore resemble a network, meaning there is less hierarchy between the disciplines. The manufacturer is equally important to the designer, and is involved in the early design stages to jointly develop a high level concept for the product.

Innovation
The governance of innovation can be characterized as turbulent. Though traditionally this turbulent process was structured by stage-gate processes, even its original developer recognizes that new models are appearing, which incorporate lots of feedback loops not only between phases but also between activities. These spiral developments can be characterized as build-test-evaluate-revise, and allow for rapid experimentation. Innovations are generally developed by committed (small) in-house teams, which

continuously revise their processes and responsibilities based on what is learned during the process. The process is therefore fully integrated. This governance domain shows a lot of similarities to Agile, which is widely used in the software industry.

6 Analysis Case-Studies

This chapter presents the homogenized findings of seven case-studies that were investigated through conducting interviews with key players involved in the projects. Paragraph 6.1 – 6.7 present the homogenized findings, the detailed interview results can be found in appendices C – G. Findings from the case studies are then aggregated and conclusions that answer the first research question are presented in 6.8. To present a high level answer to the first research question, the chapter concludes with the governance domains that were observed in the case studies (6.8.7).

Research Question	Answered in:
(1) What does the governance of a project in which 3D printing is applied currently look like?	6.8
(1a) What organizations can be recognized?	6.8.2
(1b) What are the roles and responsibilities of these organizations?	6.8.2
(1c) What project lifecycle phases can be recognized?	6.8.3
(1d) What key activities can be recognized?	6.8.4

Each case is presented with the same structure. First, an introduction is given stating the project, its purpose, the motivation to apply 3D printing, the current state of development, and an introduction to the interviewee. (subparagraph 1) Second, project characteristics are presented in a table to provide context to the type of governance that was observed. (subparagraph 2). Third, an organizational chart is presented, highlighting the roles, organizations and their relations in the project. It then describes the phases in which these organizations were involved, and what their responsibilities were. (subparagraph 3) Fourth, phases and activities are visualized and briefly elaborated. (subparagraph 4) Finally, encountered challenges and future improvements are listed. (subparagraph 5). Though the challenges and future improvements is not a research question in itself, they serve as input for the designed governance structure in chapter 8. Finally, a short conclusion is presented on what future development scenario the case implies, what the maturity of the observed process was, and which governance domain were observed (subparagraph 6).

6.1 “3D-Printing in the Circular City” Project

This paragraph presents the homogenized findings of the interview conducted for the “3D-Printing in the Circular City” Project. (see figure 28) The full interview results can be found in appendix C.

FIGURE 29 “3D-PRINTING IN THE CIRCULAR CITY” PROJECT (PICTURE OBTAINED FROM INTERVIEWEE)

6.1.1 Introduction

The 3D-Printing in the Circular City” project is a research project which investigates the possibility of using municipal plastic waste to produce functional 3D printed products that can be applied in public space. This concept is first tested in a case study in Amsterdam that resulted to the production of a bench. It is not necessarily a construction project, but does partially fulfill the functionality criterion, as the created product will be placed in public space.

The interviewee is Foteini Setaki, a PhD student at TU Delft, who is also the founder of The New Raw: a startup with services related to the circular economy and 3D printing.

This project was used as an initial validation for the created interview framework (see appendix C to I), before actors in construction projects were interviewed.

6.1.2 Characteristics

The project characteristics are highlighted in table 2.

Element Scale	Material	Printing Style	Location of production	Printed Elements	Employed Technology
Product	Concrete	**"Inside the box"**	On Site	**Stuff**	**FDM**
Building	Steel	"Outside the box"	**Off Site**	Space	SLS
	Plastic (waste)			Structure	Binder Jetting
	Nylon			Skin	
	Stone			Services	
				Site	

TABLE 2 "3D-PRINTING IN THE CIRCULAR CITY" PROJECT CHARACTERISTICS

6.1.3 Organizational Chart

The organizational chart of the 3D-Printing in the Circular City" project can be found in figure 30. Since the 3D-Printing in the Circular City" project is a research project, no formal hierarchy was present. Information on the roles and responsibilities lead to an interpretation of what it looked like. The existing roles are colored in blue, the new roles are colored in green. The same representation is applied for all other organizational charts in this chapter.

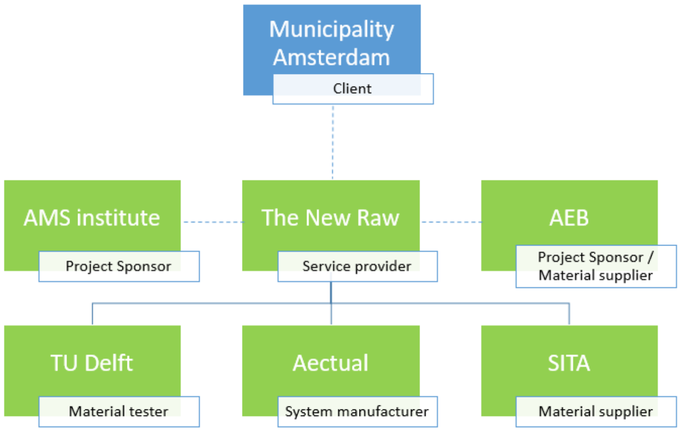


FIGURE 30 ORGANIZATIONAL CHART 3D-PRINTING IN THE CIRCULAR CITY" PROJECT

Responsibilities of actors

The service provider (The New Raw) initiated and coordinated the project and was actively involved in all phases. They were responsible for the project definition, the design of the parametric 3D model and one part of the material research. The client (Municipality) was involved in the early design phases. They did not have responsibilities in this project, though they did influence the type of product that would be printed.

Project sponsors (AMS Institute + AEB Amsterdam) were involved in the phases of technology and material development and early design. They did not have responsibilities, but did support the service provider and system manufacturer through financial contribution and through their expertise.

The material supplier (AEB Amsterdam) was involved in the (material) technology development phase. They were responsible for delivering waste materials that could be printed, and providing related expertise.

The system manufacturer (Aectual, a startup within DUS Architects), was involved during (printing system) technology development, design and manufacture. They were responsible for the manufacturing of the bench and a part of the material research. They supported the service provider in the design phase by providing knowledge on manufacturing requirements.

The material tester (TU Delft) was involved in the technology development phase. They did not have responsibilities in the project, but supported the service provider (The New Raw) by making available their laboratory to facilitate tensile and compressive tests on small batches of printed elements.

6.1.4 Phases and activities

The phases and activities of the 3D-Printing in the Circular City" Project are presented in figure 31. Phases before design are colored blue, the design phase green, and the manufacturing phase orange. The same representation is applied for all other phase diagrams in this chapter.

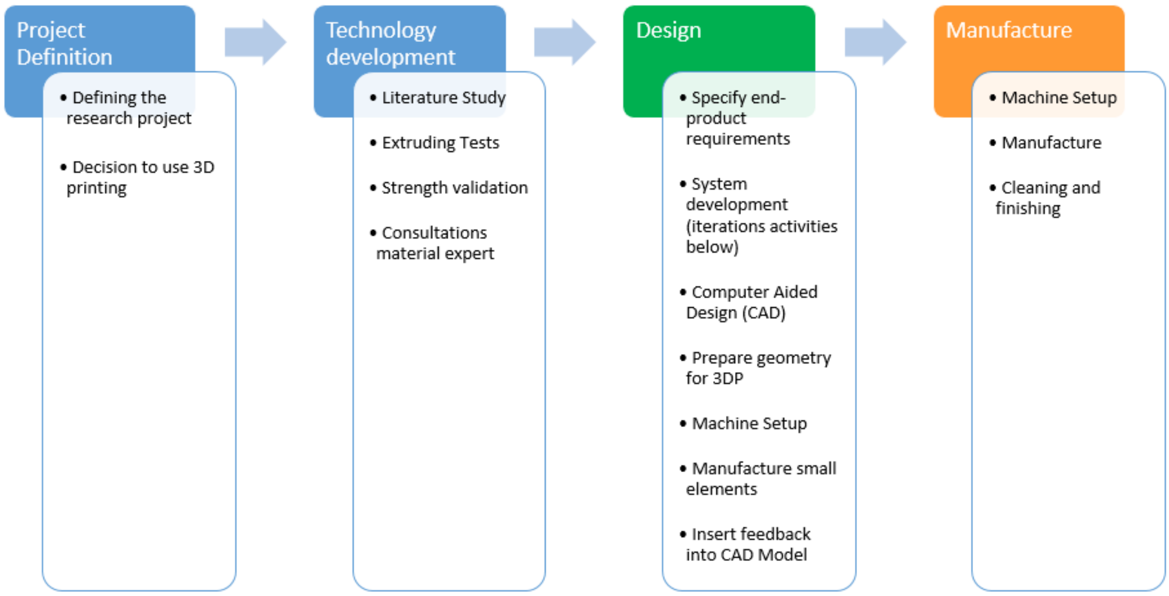


FIGURE 31 PHASES AND ACTIVITIES 3D-PRINTING IN THE CIRCULAR CITY" PROJECT

Phases
Traditional construction project phases were not applicable to this project. This can partly be explained due to the fact that it is a small scale research project instead of a construction project. The phases of the Aerospace production process however were applicable.

Though the homogenized findings indicate a linear stage-gate process, significant interaction between the phases technology development, design and manufacture were found, due to the large amount of iterations between material selection, design and manufacture.

The new phase "technology development" (prior to design) was identified, where materials were tested for their suitability for 3D printing. Additional technology development was done during the design phase.

Activities
"System development" was done during the design phase. Small pieces of the final product were printed to obtain knowledge on the capabilities of the printer and the materials. Knowledge obtained during the printing was integrated into the digital model. Several iterations were gone through before the final product was manufactured.

Post treatment in the form of polishing was required before the bench was completed.

6.1.5 Challenges and future improvement

Challenges
Verifying the printability of the digital 3D model was a technical challenge in the project. Requirements for printability constituted an uncertainty that was resolved by experience of the system manufacturer and several printing iterations. Parameters considered included printing path, time between layers and inclination angle.

Though the unique freeform shape is one of 3D printing's opportunities, the municipality saw it as an obstacle for wide scale implementation, because no standards for them developed.

Potential business cases for AEB (adding value to valueless material), municipality (objects for built environment/ reducing municipal plastic waste) and the AMS institute (research) helped to secure funding for the research project.

Adhering to building standards was not an issue in this project due to its small scale, though some initial testing was done on parts produced with the selected manufacturing technology, the strength of the full object will be verified when it becomes open to the public.

Future improvement
Having an in-house printer would have resulted in a faster system development phase, as it would allow for faster iteration cycles.

The potential client for the objects (municipality) could have been involved earlier in the process

6.1.6 Conclusion

"3D-printing in the circular city" implies the scenario 3D printed components.

The governance can best be described by a combination of the domains product design and innovation. Several iterations between design and manufacture and close collaboration with the manufacturer are characteristics of the governance of product design. The governance of innovation can also be observed. The processes could be described by a capability maturity model 1, and included lots of experimentation with materials and printing. No formal roles and responsibilities were defined. Also, the project was research oriented.

This case study provides an initial validation of the prepared interview framework for all remaining case-studies. The findings of the "3D printing in the circular city" project and other case studies in this chapter are translated towards general conclusions on what the governance of a project in which 3D printing is applied looks like in paragraph 6.8.

6.2 De Vergaderfabriek

This paragraph presents the homogenized conclusions of the interview conducted for the Vergaderfabriek project. (see figure 32) The full interview results can be found in appendix D.

FIGURE 32 THE VERGADERFABRIEK (PICTURE OBTAINED FROM INTERVIEWEE)

6.2.1 Introduction

The Vergaderfabriek is a project with the purpose of constructing a conference building using 3D printing. The client and initiator are the owners of the Slaapfabriek, a hotel in Teuge in the Netherlands. At the time of the interview, the project is in the design phase.

Besides enthusiasm for 3D printing, the client wanted to create an iconic, sustainable meeting location, which used sensing & sound technology. This resulted in 3D printing being a design requirement for the building.

The interviewee is Hugo Jager, who is originally an economist and now occupied with economical and strategic problems related to innovations and their implementation in organizations. He is a partner at Revelating, a company that provides consultancy services related to innovation. Revelating coordinated the Vergaderfabriek project.

6.2.2 Characteristics

The project characteristics are highlighted in table 3. Since at the time of the interview the project is still in its design phase, a definitive decision on the type of printed elements and location of production was not obtained during the interview.

Element Scale	Material	Printing Style	Location of production	Printed Elements	Employed Technology
Product	**Concrete**	"Inside the box"	**On Site**	Stuff	**FDM**
Building	Steel	**"Outside the box"**	Off Site	**Space**	SLS
	Plastic (waste)			**Structure**	Binder Jetting
	Nylon			**Skin**	
	Stone			Services	
				Site	

TABLE 3 PROJECT CHARACTERISTICS VERGADERFABRIEK

6.2.3 Organizational Chart

The (unconventional) organizational chart of the Vergaderfabriek project can be found in figure 33. The contract was set up by Lexence Advocaten, and allows organizations to collaborate towards realization of the project, without committing to the outcome. It could be compared to a statement of intent. This leaves space for the involved parties to realize their individual business cases within the overall project and reduces their risk exposure.

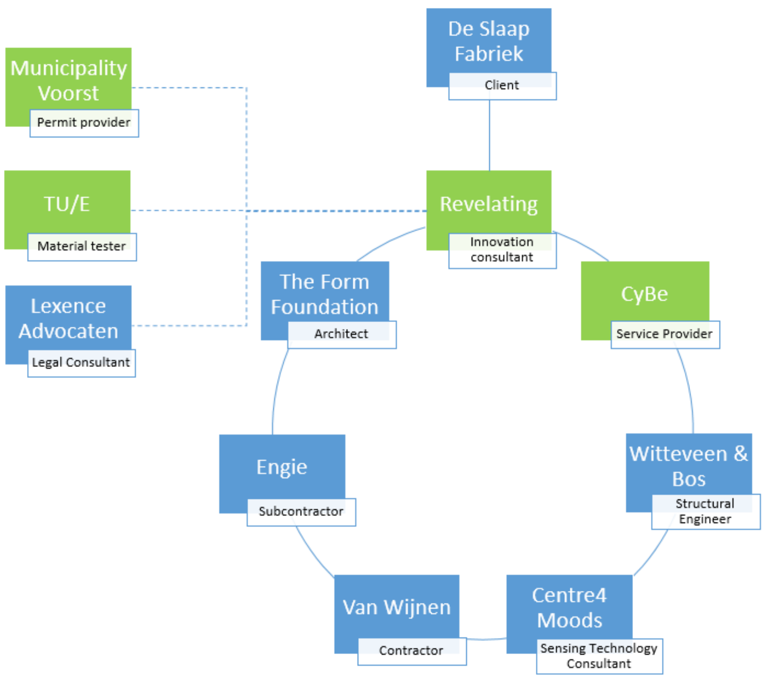


FIGURE 33 ORGANIZATIONAL CHART VERGADERFABRIEK

Responsibilities of actors

Because the contractual arrangement did not tie parties to a specific outcome, the detailed responsibilities detailed established. The interviewee highlighted that all parties collaborated actively during the design. Based on his the answers, the following interpretation on responsibilities was made.

An innovation consultant (Revelating) was involved in all project phases. He was responsible for coordinating the project process and its parallel process with the TU/E and municipality.

The Architect (The Form Foundation) was involved in all project phases. He was responsible for creating the preliminary design, and for the design integration.

The service provider (CyBe) was involved in the partner selection and the design. They were responsible for engineering and printing the concrete elements, and supported the architect in the preliminary design (during the project's hackathon).

The contractor (Van Wijnen), was involved in the design phase. They supported the architect with manufacturing expertise during the design phase.

The subcontractor (Engie) was involved in the design phase. He was responsible for providing expertise on installations.

The material tester (TU/E) was involved during partner selection and design. They are responsible for testing the material properties of the materials used by the service provider. Their testing results will be used as input for obtaining a building permit in a later design stage. Also, they were consulted in the partner selection for the purpose of cross referencing.

The permit provider (municipality) was involved in the design phase. Though they do not have responsibilities for the project, they do have power because they can grant or deny the building permit legally required for construction to commence. They were involved early in the process to increase the likelihood of them granting this permit.

6.2.4 Phases and activities

The phases and activities of the Vergaderfabriek are presented in figure 34.

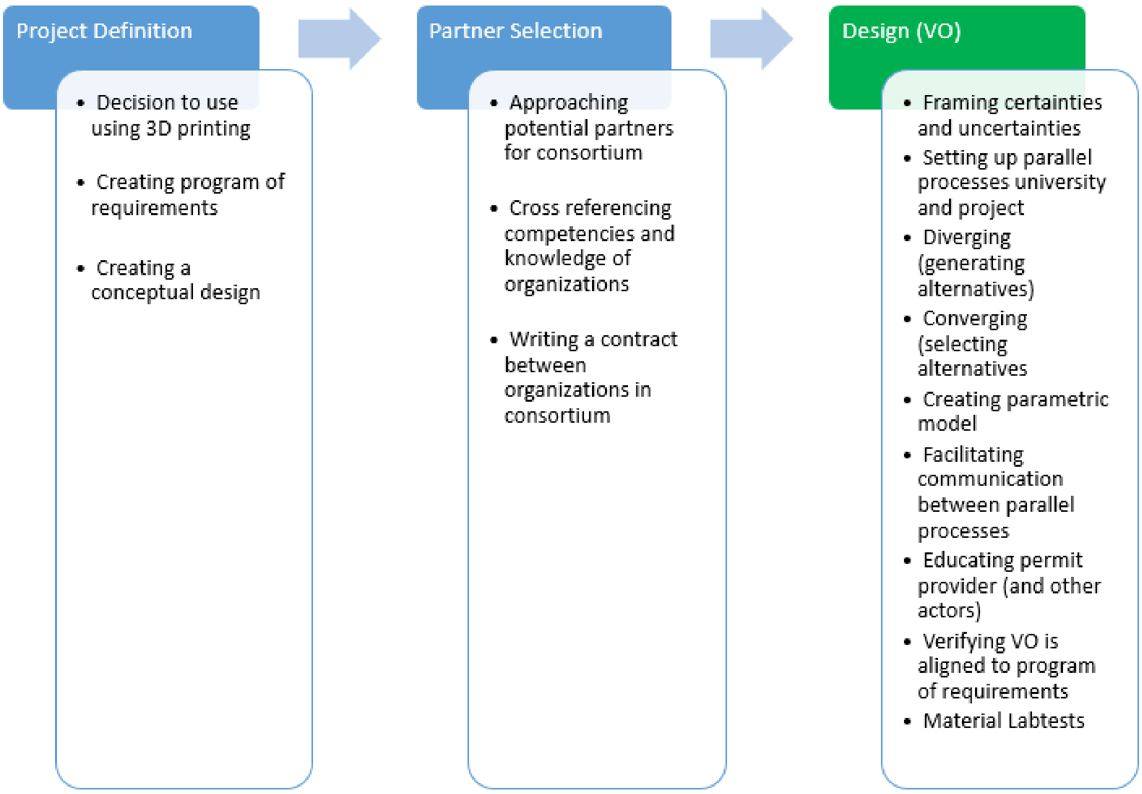


FIGURE 34 PHASES AND ACTIVITIES VERGADERFABRIEK

Phases
The identified phases are similar to that of a traditional construction process (though they are not the same).

Besides the design of the building, two more phases can be identified that could be referred to as individual "projects". These are involving and educating the permit provider and the material testing process by the material tester.

Activities
A hackathon was organized to create a conceptual design for the building.

Certainties and uncertainties were specified. This gives insight in the amount of uncertainty in the project. Project independent uncertainties can be outsourced to universities, who are actively researching the topic.

Cross referencing during the partner selection phase was done to verify the claims by the parties who offer their services. This can decrease the amount of uncertainty in the capabilities of the organizations.

During the design phase, disciplines have their own input and boundary conditions which they insert in the project design, making the design work complex and highly iterative. There are diverging phases in which ideas are generated, and converging when ideas are selected for further detailing. Further detailing can result in additional challenges and opportunities which can be used as input for the next diverging stage. The design process has gone through several of these iterations so far.

Design integration required the most effort in this project. This includes both balancing the input of all disciplines as well as designing the interfaces between printed and traditionally manufactured components. Communicating through whiteboard sketches during design meetings was an important tool in the project.

6.2.5 Challenges and Future improvements

Challenges
Within the boundary conditions set by the robots, material development is the key issue and uncertainty in the project. This uncertainty plays a key role throughout the project.

A key issue for the 3D printed building is acquiring a building permit. The experience of CyBe is used as input for the design, but the data required for final verification is provided by the TU/E. The municipality is involved early to increase chances of obtaining a permit. Verification could be done in three stages: during the design, during manufacturing and on the final product.

3D printing allows for customization which individual disciplines can use to improve their functionality. However, most actors are not used to designing in this fashion and have to be educated on what is possible. They have to learn to think outside of their conventional paradigm of designing. If more people are involved in this process and their knowledge and experience with printing is low, this educating can become very time consuming. (this also holds true for the municipality).

Another challenge in utilizing additional functionality for disciplines is that each discipline provides unique input, which can be in conflict with the input of other disciplines. Integrating these inputs, weighing design alternatives and converging to a single design becomes more complex if more parties are involved.

Creating a level playing field between disciplines can be a challenge when actors are accustomed to the traditional (more hierarchical) way of working.

Due to a large degree of uncertainty at the start of the project (3D printing being a new technology), a hard deadline or detailed cost estimation is more difficult to make. Time also has to be spent on reducing the uncertainty, which is not the case for traditional projects. A measure for this uncertainty are Technology Readiness Levels (TRL).

Future improvement
The process went well, though the existing knowledge is now more expansive. (uncertainty is reduced through experience). This means that a next similar project would be more efficient.

A client that has a clear vision, requirements and that can set the right frames at the start of a project is key to realize it.

6.2.6 Conclusion

The Vergaderfabriek implies the scenario 3D printing the majority of a building.

Though the current phase the project was in was described by VO (a standardized phase for a construction project), the governance can best be characterized as a combination of the domains product design and innovation.

Elements that describe the governance domain product design are the continuous diverging and converging iterations within the initial design phases, and a "level playing field" (network approach) was purposefully created between all project participants. These did not only integrate designer and manufacturer, but also the engineering and contractor. Later iterations between the VO and DO were anticipated on by the project manager. level 2. The overall direction of the project was defined, though the activities were done in an ad-hoc manner. The innovation domain can be observed in the laboratory tests on printed materials that was done in parallel to the design process for the building.

6.3 R&Drone Laboratory

This paragraph presents the homogenized conclusions of the interview conducted for the Vergaderfabriek project. (see figure 35) The full interview results can be found in appendix D.

FIGURE 35 R&DRONE LABORATORY (Saunders, 2017)

6.3.1 Introduction

The R&Drone laboratory in Dubai will be a facility for research and development related to drones and 3D printing, financed by the client DEWA. Aligned with Dubai's vision for printing 25% of their buildings in 2030, one of the requirements for this facility was that it should be 3D printed. At the moment of the interview, the project is in the final stages of construction.

Berry Hendriks is the founder of CyBe Construction, a service provider specialized in the 3D printing of concrete. At the R&Drone laboratory, they have recently delivered the (on site) printed concrete components for the façade and roof structure.

6.3.2 Characteristics

The project characteristics are highlighted in table 4. Some of the walls that were constructed were loadbearing. This was achieved by printing the formwork for some elements in the outer wall, installing reinforcement and casting in conventional concrete, creating a stable structural scheme.

Element Scale	Material	Printing Style	Location of production	Printed Elements	Employed Technology
Product	**Concrete**	"Inside the box"	**On Site**	Stuff	**FDM**
Building	Steel	**"Outside the box"**	Off Site	**Space**	SLS
	Plastic (waste)			**Structure**	Binder Jetting
	Nylon			**Skin**	
	Stone			Services	
				Site	

TABLE 4 PROJECT CHARACTERISTICS R&DRONE LABORATORY

6.3.3 Organizational chart

The organizational chart of the overall project R&Drone laboratory can be found in figure 36.

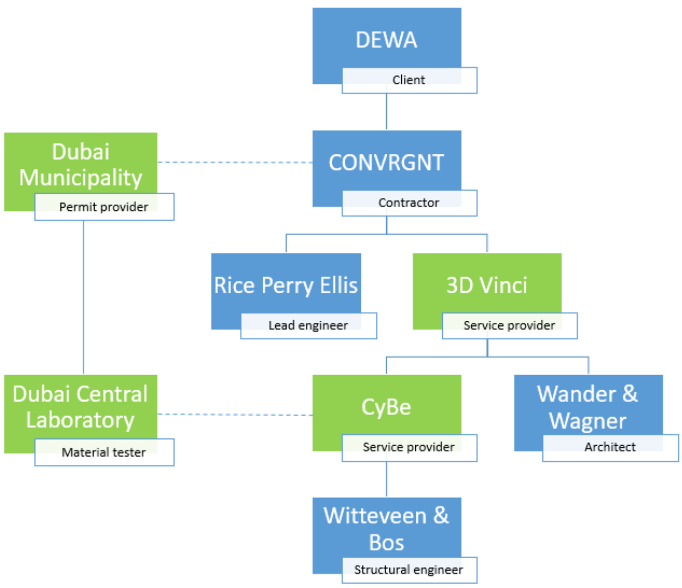


FIGURE 36 ORGANIZATIONAL CHART R&DRONE LABORATORY

Responsibilities of actors

The client (DEWA) was involved in the project definition phase and responsible for creating tender documents, The contractor (CONVRGNT) was involved in all phases after project definition. They were responsible for the delivery of the project as specified by the client tender documents. They set up an organization to realize them, distributing responsibility for work packages to other organizations. They were responsible for the acquisition of a building permit.

The service provider (3D Vinci) was involved in the partner selection phase. They were (contractually) responsible for delivering the 3D printed works, but outsourced this responsibility to an architect (Wander & Wagner) and service provider (CyBe).

The architect (Wander & Wagner) was involved in the design phase. He was responsible for the conceptual design of the printed elements.

The service provider (CyBe) was involved in the partner selection, design and manufacturing phase. They were responsible for engineering and (on site) manufacturing of the printed elements as (conceptually) designed by the architect. They outsourced structural design work to Witteveen & Bos.

The engineer (Witteveen & Bos) was involved in the design phase. They were responsible for incorporating structural principles into the parametric (Grasshopper) model and required structural calculations for the printed elements.

The material tester (Dubai Central Laboratory) was involved in the design phase, and was responsible for obtaining material characteristics for service provider's materials, through laboratory tests.

6.3.4 Phases and activities

The phases and activities related to the 3D printed components of the R&Drone laboratory are presented in figure 37.

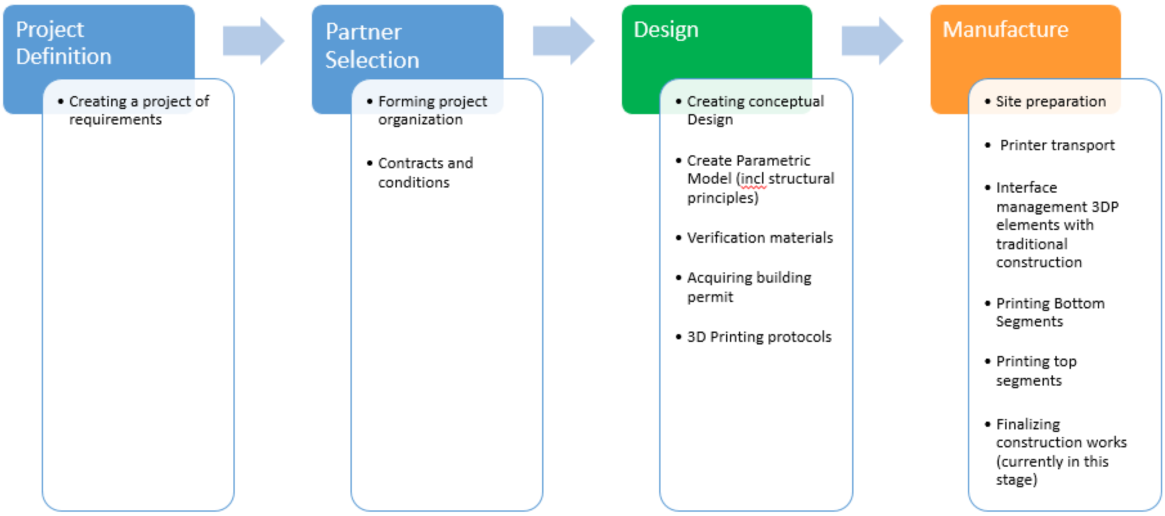


FIGURE 37 PHASES AND ACTIVITIES R&DRONE LABORATORY

Phases
CyBe uses a specific process for their projects, inspired by systems engineering. It consist of five phases: orientation, design and engineering, transport and preparation, printing, and finalizing construction.

Activities
A parametric model was created with incorporated structural principles. The requirements included offset, width, contour lines, and column dimensions for sufficient reinforcement. Developing this tool took six weeks now, but another design with the same model would only take 2 days in a somewhat similar project (greatly reducing lead-time).

The permit was granted in an early stage. It has to be noted that in Dubai the requirements for obtaining a permit are lower than in Europe. Creative thinking is often done during construction, rather than during the design stage.

During construction, the 3D printed elements had to interface with the traditionally constructed elements. CyBe made 3D printing protocols ("Werkplannen") to plan the required activities on site. This was an important element since the communication was not always transparent between the involved organizations.

Annex D of the EN1990 "Design by assisted testing" from the Eurocode was used for verification of the printed components. The material properties were obtained through laboratory tests, and structural calculations with these properties were done.

6.3.5 Challenges and future improvement

Challenges
The design integration (between printed and conventional elements) took substantial effort in a later part of the project because the topic did not receive sufficient attention during the early stages of the project.

CONVRGNT initial approach was to manage the project in a traditional way. The governance was set up in a very hierarchical way, in which actors only talked to their immediate hierarchical links. Later in the project this caused a large discrepancy in the overall planning and the planning for the 3D printed works. The discrepancy was amplified by the cultural differences. CyBe has a more western culture, in which emphasis and creativity is put on the design and engineering work. Creative thinking during construction is then limited. In middle eastern culture however, the emphasis and creative thinking is often done during the construction process.

There is a difference between bruto printing speed (sole printing of the elements) and netto printing speed (includes waiting time, mobilization of equipment). The latter can be significantly higher than the previous.

Several months into the project, the project organization reformed, allowing for communication between CONVRGNT and CyBe. Several legal proceedings occurred in the transition process.

Future improvement
The employed process worked well for CyBe, if in the future similar projects will be requested the design can go a lot faster (because the parametric model can be re-used). Hendriks sees several future opportunities for his technology.

Firstly there could be a different design process in which the computer generates design alternatives instead of a human. This allows for more iterations and feedback loops in the design, resulting in a faster overall process.

Secondly, there is an opportunity for more large scale business cases ("seriebouw"). Instead of a large VINEX area where all houses are the same, there can still be a degree of customization. Different requirements from individual clients can be quickly incorporated in the parametric model (the created model includes as input the orientation to the street and sun, surface area's for rooms, structural principles, and external contour lines at three heights). Based on this start, you only have to do the last 20% of the design work yourself. By developing a full business case you take advantage of the generative abilities of the parametric Grasshopper model.

6.3.6 Conclusion

The R&Drone laboratory implies the scenario in which a number of 3D printed components is applied in a project.

Though the current phase the project was in was described by VO (a standardized phase for a construction project), the governance can best be characterized as a combination of the domains construction project, product design and innovation.

For the overall project, the domain construction project was observed. A rigid stage-gate process and hierarchical relationships between project participants. For the 3D printed components, a combination between product design and innovation was found. The manufacturer aimed at a collaboration with the main contractor. Lots of innovation elements can also be observed, both for the technology (laboratory tests of materials) and the processes (designing the components, on-site activities and workflow). At the start of the project, the processes had a capability maturity model of 1, activities were managed ad-hoc.

6.4 MX3D Bridge

This paragraph presents the homogenized conclusions of the two interviews conducted for the MX3D bridge. (see figure 38) The full interview results can be found in appendix F.

FIGURE 38 MX3D BRIDGE (Laarman, 2017)

6.4.1 Introduction

The MX3D bridge is a project that aims to 3D print a functional bridge in stainless steel and place it in the center of Amsterdam, by using 6 axis industrial robots equipped with welding equipment. It is coordinated by MX3D, a company that develops robotic 3D printing technology in steel.

Two interviews were conducted for the findings of this paragraph. The first interviewee was Bertrand Le, an associate in Arup who led the Arup design team that developed a preliminary structural design (VO) for the bridge. The second interviewee was Tim Geurtjens, the CTO at MX3D.

At the time of the interview (June 2017), the project was in the initial construction phases.

6.4.2 Characteristics

The project characteristics are highlighted in table 5.

Element Scale	Material	Printing Style	Location of production	Printed Elements	Employed Technology
Product	Concrete	"Inside the box"	On Site	Stuff	FDM
Building	**Steel**	**"Outside the box"**	**Off Site**	Space	**SLS**
	Plastic (waste)			**Structure**	Binder Jetting
	Nylon			Skin	
	Stone			Services	
				Site	

TABLE 5 PROJECT CHARACTERISTICS MX3D BRIDGE

6.4.3 Organizational Chart

The organizational chart of the MX3D project (see figure 39) is unconventional for a bridge. MX3D is a startup that has attracted investors to develop their metal printing technology. To showcase this technology, they realize products and projects, which are then sold to clients. This means that the municipality, a potential buyer for the bridge, is involved in the project but does not have the authority to steer it.

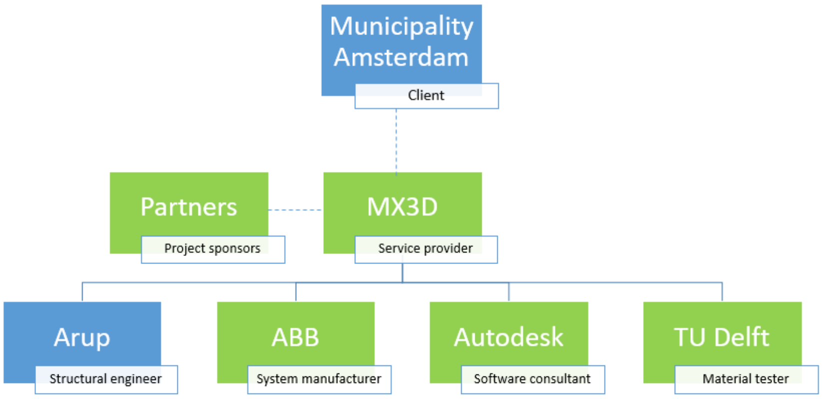


FIGURE 39 ORGANIZATIONAL CHART MX3D BRIDGE

Responsibilities of actors

The service provider (MX3D) was involved in all project phases. They were responsible for developing the technology, design, engineering and delivery of the bridge. Also, they coordinated and managed the overall project. The technology development was done in collaboration with multiple partners.

Project sponsors contributed financially and provided expertise to the technology development.

The software consultant (Autodesk) was involved in the technology development. They provided expertise related to the used software.

The system manufacturer (ABB) was involved in technology development. They supplied the service provider with robots and offered related expertise.

The material tester (TU Delft) was involved during the technology development. They were responsible for conducting laboratory tests on small printed elements from MX3D.

The structural engineer (Arup) was involved in the design phase. They were responsible for making the structural design (VO) and the development of a structural verification strategy.

The contractor (Heijmans) was involved in the project definition. They supported the service provider in making the initial design.

6.4.4 Phases and activities

The phases and activities of the MX3D bridge are presented in figure 40.

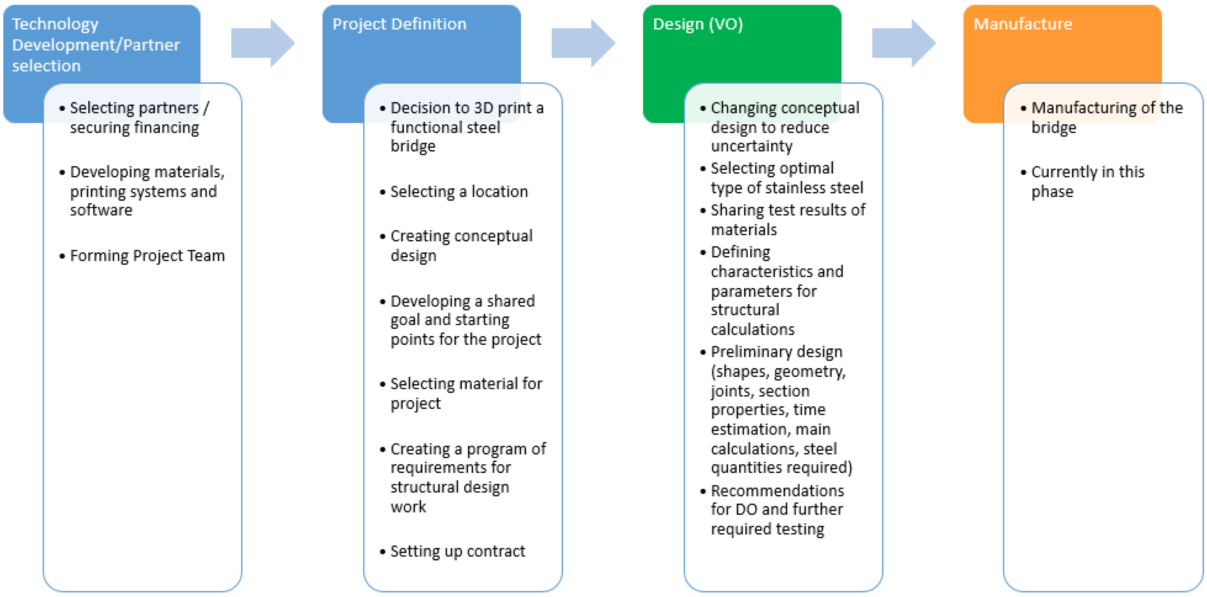


FIGURE 40 PHASES AND ACTIVITIES MX3D BRIDGE

Phases
Construction was started immediately after the VO, bringing construction much closer to the design.

Activities
Arup supported MX3D in creating a program of requirements for the structural design, including starting points and assumptions.

The conceptual design was changed to reduce the degree of uncertainty in the project.

Verification during the design stage was done through a simplified, structural 3D model. Assumptions were made on parameters, based on the material properties that were identified through laboratory tests. Additional testing will be required during manufacturing.

6.4.5 Challenges and Future improvement

Challenges
The starting point and perspective for this project was different for MX3D and Arup. MX3D approached the project as an artefact that would also function as a bridge. Arup viewed it as a bridge with good aesthetics. The latter introduces a significant amount of additional requirements (open to public, demonstration of safety, building permits). These two perspectives took some time to converge to a shared prevailing perspective.

Future improvement
Involving the municipality more often would be helpful to increase chances of realizing a bridge that is demonstrated to be safe and open to the public.

A stable, committed project team working continuously on realization of the project would be an improvement. The design team changed as the project went forward (actors left and joined). For the project, it would have been better to upfront specify the skills and expertise that was required and selecting a stable project which had these capabilities and could execute the works.

6.4.6 Conclusions

The MX3D Bridge implies the scenario 3D printing the majority of a building, though the structure was a bridge rather than a building.

The governance can best be characterized as a combination of the domains product design and innovation. Product design elements were the collaboration and early engagement of the disciplines in the design process, which collaborated closely during the project. Innovation elements were the experimentation and iterations between design, manufacture and testing. Processes evolved in an evolutionary way and specific activities were defined in an ad-hoc manner. This seems to indicate a maturity level 1 of the capability maturity model.

6.5 The Great Pagoda

This paragraph presents the homogenized conclusions of the interview conducted for the Great Pagoda project. (see figure 41) The full interview results can be found in appendix G.

FIGURE 41 THE GREAT PAGODA PROJECT (Wei, 2017)

6.5.1 Introduction

The Great Pagoda is a renovation project of the "Great Pagoda" in Kew Gardens in the United Kingdom. The original structure included symbolic dragons on the corners of each roof, which were lost shortly after installation. During the renovation the client (Historic Royal Palaces) aims to recreate these dragons (approximately 80, varying in size and shape), based on the existing paintings of the pagoda. At the moment of conducting this interview (June 2017), the dragons are in the manufacturing stage and the pagoda is expected to be opened in 2017.

The motivation for 3D printing was to reduce the project risks associated with making the dragons with conventional methods (the original plan was to manually carve the dragons from wood). These risks were related to the required time, the labor cost and the weight of the wooden dragons on the old structure. 3D printing offered several benefits in this project:

- Automating the process (speed increased, lower labor cost)
- Weight reduction (lattice structure of nylon were considered that are a lot lighter than solid wood)
- Allows for complexity and customization at little additional cost (The dragons on the rooftops would become slightly smaller towards the top of the building)

The interviewee is Salomé Galjaard, a senior designer and digital fabrication expert within Arup. Arup was approached by the client to provide consulting services related to the feasibility of 3D printing and other digital fabrication methods these dragons, instead of manually carving them from wood.

6.5.2 Characteristics

The project characteristics are highlighted in table 6. The dragons will be manufactured by 3D systems. The exact technology they intend to use could not be specified by the interviewee.

Element Scale	Material	Printing Style	Location of production	Printed Elements	Employed Technology
Product	Concrete	**"Inside the box"**	On Site	**Stuff**	FDM
Building	Steel	"Outside the box"	**Off Site**	Space	**SLS**
	Plastic (waste)			Structure	Binder Jetting
	Nylon			Skin	
	Stone			Services	
				Site	

TABLE 6 PROJECT CHARACTERISTICS GREAT PAGODA

6.5.3 Organizational chart

The organizational chart for Great Pagoda project can be found in figure 42.

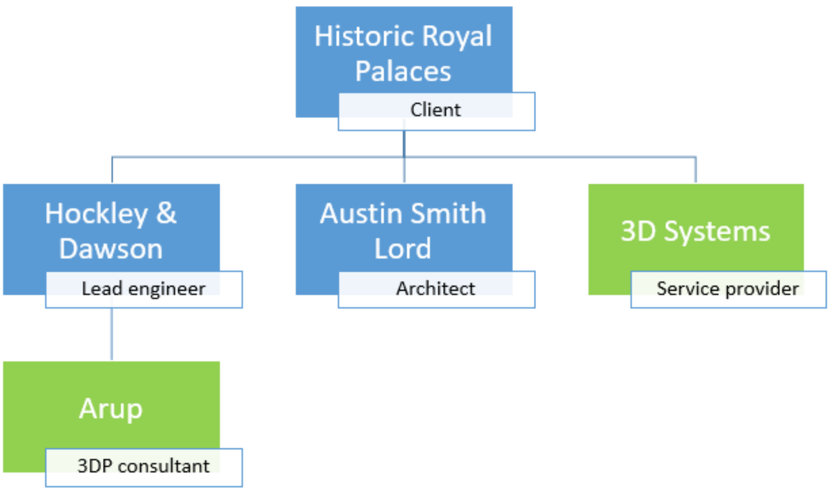


FIGURE 42 ORGANIZATIONAL CHART GREAT PAGODA

Responsibilities of actors
The 80 dragons were part of a larger renovation project. The responsibilities of the main actors directly involved with the manufacturing of the dragons were as follows:

The 3D printing consultant (Arup) was involved in the feasibility phase. They were responsible for evaluating traditional and 3D manufacturing methods and later a technology review. They also provided design recommendations for the dragons and their connections to the overall structure.

The service provider (3D Systems) was involved in the design and manufacturing phase. They were responsible for the design, engineering and manufacturing of the dragons. The manufacturer being responsible for the engineering was nog in the original plan, but since it was a decorative element, they were willing to expand their service to this domain.

It is likely that the brackets that connect the dragons to the overall structure were designed and manufactured in collaboration with the lead engineer. (Hockley & Dawson).

6.5.4 Phases and activities

The phases and activities related to the Dragons at the Great Pagoda are presented in figure 43.

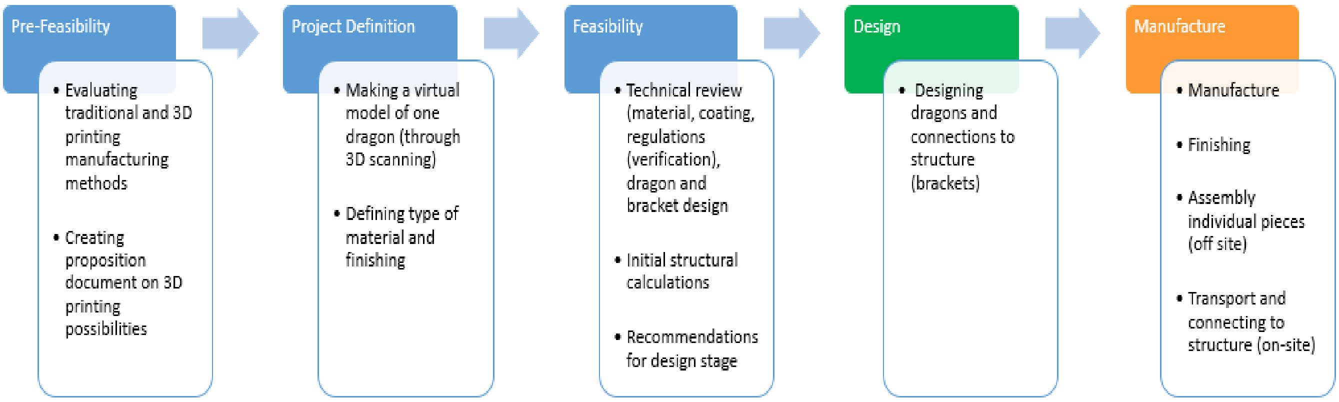


FIGURE 43 PHASES AND ACTIVITIES GREAT PAGODA

Phases
The initial phases are similar to a conventional project, though the design and manufacturing of the dragons are more integrated (and done by the same organization).

The feasibility phase was not previously found in projects. This evaluated the risks and opportunities associated with 3D printing, and later a technology review.

Activities
An interface can be identified between the design of the dragons, and that of the overall structure, because it has to be connected to it. This requires collaboration between the engineer for the overall project and the service provider.

6.5.5 Challenges and future improvements

Challenges
Though the process went well, Arup did not have experience with having a producer involved in the project that can potentially take over design services.

The project was complex due to many new elements. Through good communication this did not become an issue.

Structural verification during the design phase was done by Arup, by applying loads to a virtual model of one of the dragons. It is not clear what type of remaining verification/testing 3D systems is planning to do during manufacturing and on the final product.

A future challenge for Arup could entail competition from producers that deliver design services at a very low cost (like Philips for lighting). Whether the potential reduction in quality of design will be considered an issue will depend on the client. An important element to consider for potential future competitors (like producers and Autodesk) is that even though they could provide (or buy) services that overlap with the services of engineering firms like Arup, these activities are not necessarily intrinsically connected to other parts of these organizations, and it is unlikely they the same passion for design and engineering work. They do have more financial resources available with which they can invest in these services. Firms like Philips and Autodesk sells products, while engineer firms sell hours.

Future Improvements
An opportunity could arise when these players start to collaborate in projects more closely, where each actor does more work in his or her own specialism. This allows for better mutual understanding of the involved disciplines.

The process went well, the relation with the client was very good. Galjaard would have liked to continue working on the project during the design stage.

6.5.6 Conclusion

The Great Pagoda implies the scenario 3D printed components, because the 3D printed dragons can be considered as a component integrated in the overall structure.

The governance can be characterized by a combination of the domains construction project and product design. Innovation of technology was not found, since the manufacturing processes of 3D systems were mature (capability maturity level 5). The overall renovation project had clearly defined roles and responsibilities and likely followed the traditional procedures. For the dragons elements from product design could be observed. The manufacturer was involved at an early stage of the design process (and eventually took responsibility for the design).

6.6 Post Aix-en-Provence School

This paragraph presents the homogenized findings of the 3D printed post of a school in Aix-en-Provence. The answers for the interview were collected through a survey, instead of a face to face interview. The results of this survey can be found in Appendix H.

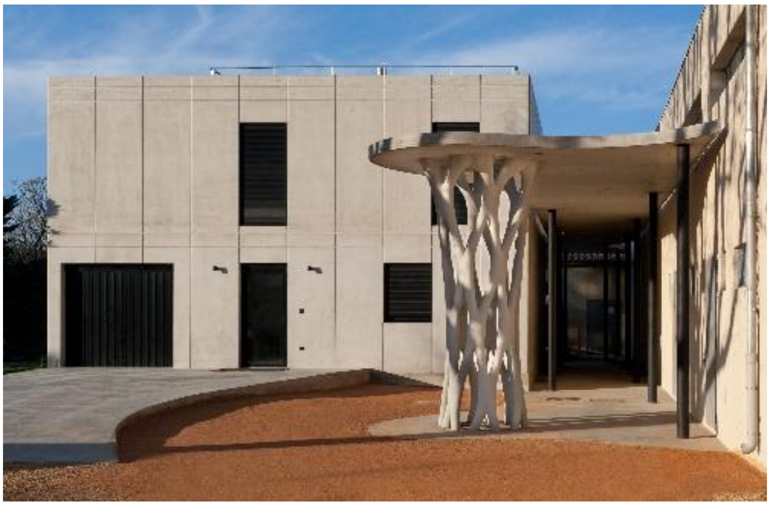


FIGURE 44 POST AIX-EN-PROVENCE SCHOOL (XTreeE, 2017)

6.6.1 Introduction

The Post Aix-en-Provence school is a project in France, where a freeform concrete post was integrated in the overall school building. The project is currently finished and therefore a fully mature example of a project in which 3D printing was successfully applied.

The architect of the project, Marc Dalibard, wanted to create a highly complex shape for the post in the Aix en Provence school, for which 3D printing was most suited.

The interviewee is Nadja Gaudilliere, project supervisor at XtreeE. XtreeE is a French company that develops advanced large-scale concrete 3D printing technology for the construction industry.

6.6.2 Characteristics

The project characteristics are highlighted in table 7.

Element Scale	Material	Printing Style	Location of production	Printed Elements	Employed Technology
Product	**Concrete**	"Inside the box"	On Site	Stuff	**FDM**
Building	Steel	**"Outside the box"**	**Off Site**	Space	SLS
	Plastic (waste)			**Structure**	Binder Jetting
	Nylon			Skin	
	Stone			Services	
				Site	

TABLE 7 PROJECT CHARACTERISTICS POST AIX-EN-PROVENCE

After validating this classification with Gaudilliere, it was mentioned that though FDM is the overall term described for concrete printing, technically speaking it cannot be classified as such because there is no material fusion involved.

6.6.3 Organizational Chart

The organizational chart for the Post Aix-en-Provence can be found in figure 45.

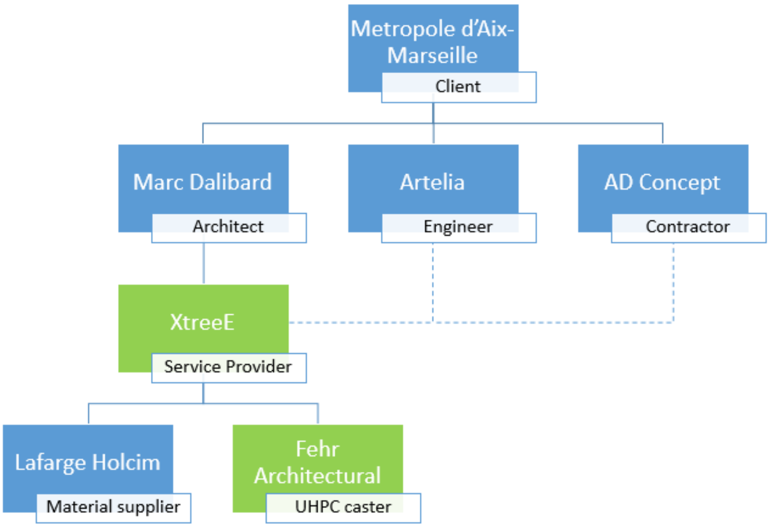


FIGURE 45 ORGANIZATIONAL CHART POST AIX-EN-PROVENCE

Responsibilities of actors
Like the great Pagoda, the post was a part of a larger project. Responsibilities of the organizations involved directly with the printed post were the following:

The architect (Marc Dalibard) was the manager of the overall project. He was responsible for defining the post (3D printed product) and providing relevant information for the service provider.

The service provider (XtreeE) was involved in technology development, design and manufacturing. They were responsible for the design and manufacturing of the printed post. Additionally, they supervised later on site assembly of the parts. The design of the geometry and manufacturing files was done with the support of the project engineer (Artelia) and UHPC caster (Fehr Architectural).

The project engineer (Artelia) was involved in the design and manufacturing phase. They were responsible for verifying the strength and stability of the printed post and defining the load case on which a topological optimization was based. They supported the service provider for their assembly and fabrication strategy.

The material supplier (LaFarge Holcim) was involved in the technology development and manufacturing phase. They were responsible for supplying the UHPC for the printed envelope of the parts to the service provider.

The UHPC caster (Fehr Architectural) was involved during the design and manufacturing phase. They were responsible for casting UHPC (which requires a license) in the printed envelope and supported XtreeE in the development of their fabrication strategy.

6.6.4 Phases and activities

The phases and activities of the Post Aix-en-Provence are presented in figure 46.

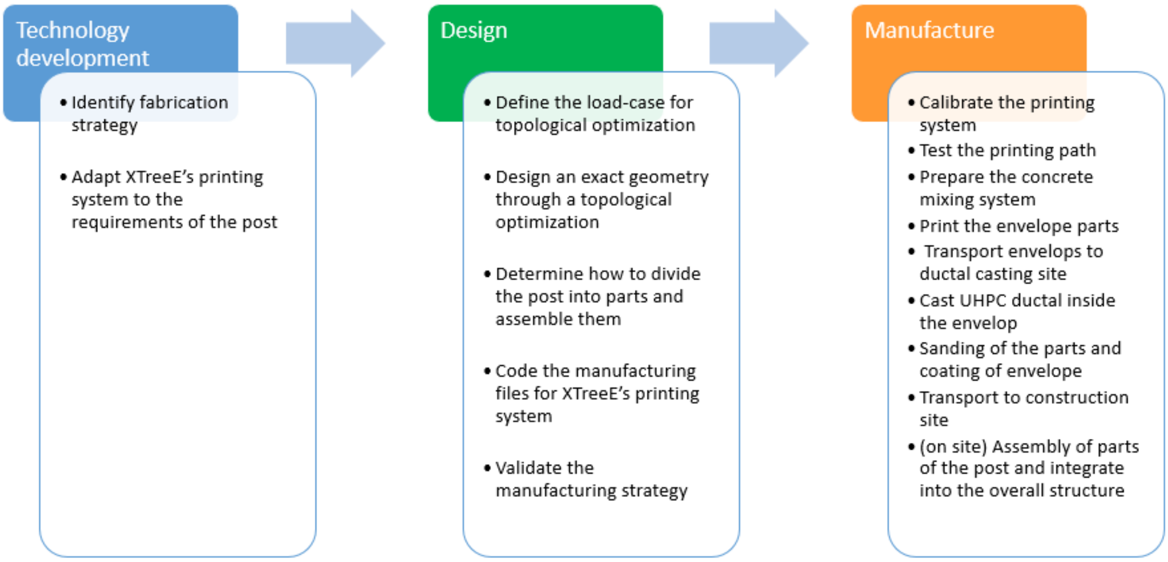


FIGURE 46 PHASES AND ACTIVITIES POST AIX-EN-PROVENCE

Phases
Though technology development was largely done prior to starting the project, the fabrication strategy and printing system was calibrated to the requirements of the project.

Activities
The fabrication strategy did not just contain how to verify the structural integrity, but also how to split up the total column into parts that could be assembled in a later stage.

A load case was used as input for a topological optimization for the form of the column.

Safety was demonstrated by casting UHPC Ductal (verified material) in a printed envelope.

Prior to final manufacturing, some small scale calibration was done. The parts were assembled on site by the contractor, under supervision of the service provider.

6.6.5 Challenges and future improvements

Challenges
The absence of construction regulations regarding 3D printing was a major issue. Therefore, alternative methods were found to guarantee safety and structural integrity. Close collaboration with the project engineer (who had knowledge on the codes) resulted in a manufacturing process that allowed XtreeE to stay within the existing regulations.

A second challenge was the need for a (specialized) certified organization to cast the UHPC ductal in the envelope. This means that the element had to go through production phases at different locations, requiring additional transportation.

Future improvements
The establishment on construction regulations for 3D printed structures would greatly simplify the process of verifying the structural integrity and safety. Secondly, having all production facilities at the same location would reduce logistical complexity and increase the speed.

6.6.6 Conclusion

The Post Aix-en-Provence project implies the 3D printed components scenario, since the post was a part of a larger construction project.

The governance can be characterized as a combination between the domains construction project, product design and innovation. The overall construction project likely followed the traditional phases. For the 3D printed post, a combination of product design and innovation can be found, with the post being designed as a product and the technology required for the steep inclination angles, size and assembly following an innovation approach. The processes indicate a capability maturity level 2.

6.7 Landscape House

This paragraph presents the homogenized conclusions of the interview conducted for the Landscape House. (see figure The full interview results can be found in appendix I.

FIGURE 47 LANDSCAPE HOUSE (Tess, 2016)

6.7.1 Introduction

The Landscape House is a project in Amsterdam initiated by Janjaap Ruijssenaars from Universe Architects. 3D printing was considered here to manufacture the double curved surfaces on the corners of the building. The project has undergone an extensive R&D phase and is currently looking for investments for the final realization.

The motivation for printing was the architect's wish to have complex double curved surfaces on the corners of the building, which were very expensive to manufacture using conventional manufacturing methods.

The interviewee is Chris Jonker, tender manager at BAM Bouw en Techniek. BAM Group is a large Dutch internationally operating contractor. BAM contributed to the R&D phase that was required to apply 3D printing for the Landscape House.

6.7.2 Characteristics

The project characteristics are highlighted in table 8.

Element Scale	Material	Printing Style	Location of production	Printed Elements	Employed Technology
Product	Concrete	**"Inside the box"**	On Site	Stuff	FDM
Building	Steel	"Outside the box"	**Off Site**	Space	SLS
	Plastic (waste)			Structure	**Binder Jetting**
	Nylon			**Skin**	
	Stone			Services	
				Site	

TABLE 8 PROJECT CHARACTERISTICS LANDSCAPE HOUSE

6.7.3 Organizational Chart

No formal organizational structure was formed for the project. The organizational chart found in figure 48 represents the relations between the organizations based on financial remuneration during the current technology development phase required for the double curved surfaces to be printed.

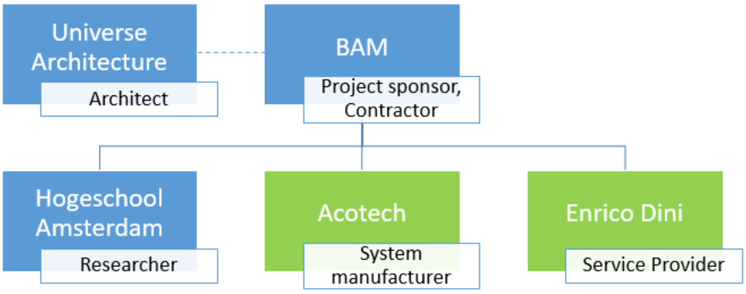


FIGURE 48 ORGANIZATIONAL CHART LANDSCAPE HOUSE

The architect (Universe Architecture) initiated the project and was responsible producing the initial conceptual design. They continued to look for partners to realize this design.

During the technology development phase that followed, all parties have worked together towards realization of the project, without a clear hierarchy or division of responsibilities.

Several other parties have made contributions to the design of the project, but did not have an active role in the R&D phase described in this interview.

6.7.4 Phases and activities

The phases and activities of the Landscape House are presented in figure 49.

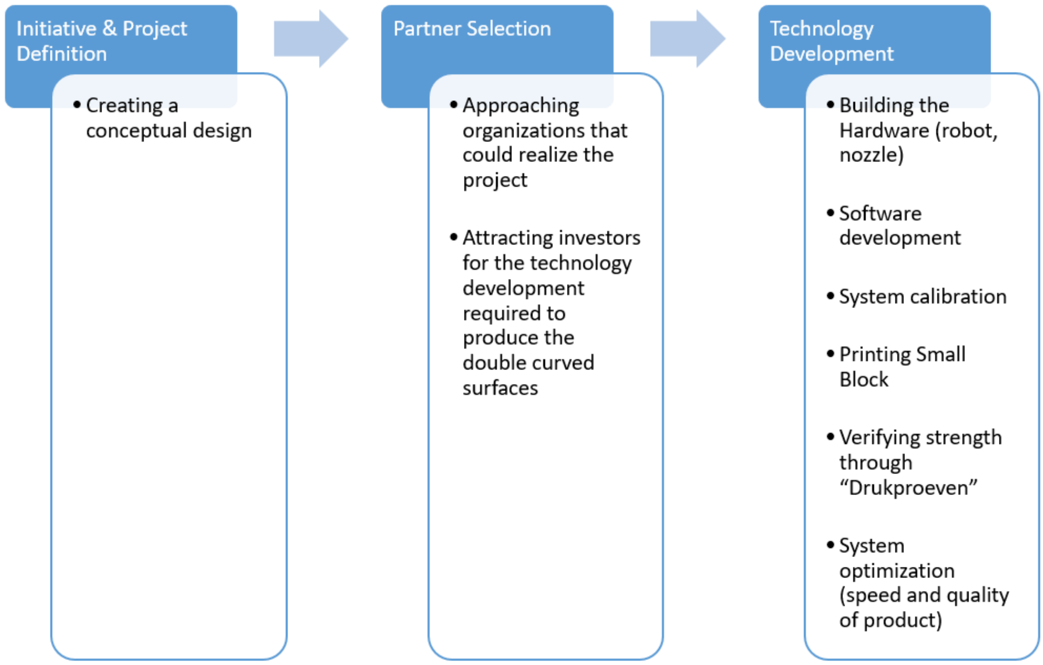


FIGURE 49 PHASES AND ACTIVITIES LANDSCAPE HOUSE

Information provided by the interviewee was primarily regarding the technology development phase. This consisted of taking an existing technology (Dini's D-Shape), replacing the old system with an Acotech industrial robot, and developing this system so it was able to produce the double curved surfaces required in the conceptual design.

6.7.5 Challenges and future improvements

Challenges

The fine tuning of all manufacturing parameters to optimize product quality and speed took a substantial amount of effort.

It is difficult to innovate within the construction industry. Firstly, contractors generally don't have R&D departments. They apply innovation when it is required for a project. This means innovation in construction is mostly a project specific activity. Secondly, particularly for BAM utilities project, requirements are unique and constantly changing, making it difficult to innovate within existing standard processes (often it is the suppliers that innovate their components). BAM prefers to have a large amount of standardized "components" which can be combined in creative ways to meet project demands. These components have been similar over the last 20 years and will likely continue to be so in the future.

Future improvements

It is important that for future projects 3D printing is a means to realize project objectives, rather than a goal in itself. At the moment, the motivation for organizations to apply 3D printing is mostly because it is "hip" and that they want to be first. For the dragons described in the Great Pagoda project clear advantages can be observed, because here it is a means (that was cost efficient). People using 3D printing as a goal in itself may be required to bring the technology forward, but it is not a sustainable business model. It is then likely to die out as soon as the "newness" of the first couple of examples fades off. BAM's perspective is to create buildings with a high quality at low cost, therefore being more pragmatic. As soon as printing is a means that is more cost efficient or provides more value than traditional manufacturing methods for a project, it has value for BAM. Currently, 3D printing is not able to do this.

6.7.6 Conclusion

The Landscape House implies the 3D printed components scenario

The governance found can be described as a combination of the domains construction project and innovation. The project was designed by an architect who then looked for a contractor to build it, resembling a clear split between design and construction. The processes described in this case study mostly resemble innovation, in which the technology required to manufacture the freeform shapes was developed. Elements that demonstrate this is lots of (iterative) experimentation with manufacturing parameters and testing, and an ad-hoc managed process. The process was started from the ground up, indicating a capability maturity level 1.

Findings of the Landscape house and other case studies in this chapter are translated towards general conclusions on what the governance of a project in which 3D printing is applied looks like in the next paragraph.

6.8 Conclusion

This chapter describes the identified project characteristics (6.8.1) and continues to answer the sub questions of the first research question on what the governance of a 3D printing project looks like in a descriptive manner, by presenting aggregated information on the governance elements observed in the case studies (6.8.2 – 6.8.4). Challenges (6.8.5) and future improvements (6.8.6) are observed in the case studies are presented, which serve as input for the design of a project governance structure in chapter 8. To provide a generalized conclusion to the first research question, an overview of the observed governance domains is finally presented and linked to the two future development scenario's. (6.8.7). Before going into the details however, key observations that are considered the most relevant are now stated.

Research Question	Answered in:
(1) What does the governance of a project in which 3D printing is applied currently look like?	6.8
(1a) What organizations can be recognized?	6.8.2
(1b) What are the roles and responsibilities of these organizations?	6.8.2
(1c) What project lifecycle phases can be recognized?	6.8.3
(1d) What key activities can be recognized?	6.8.4

6.8.1 Project Characteristics

The characteristics of each project show that a wide variety of approaches is possible for applying 3D printing in a construction project. Besides the predefined characteristics (see 4.4), two additional characteristics were identified. Conclusions on each category is presented in this paragraph.

Element Scale
5 out of 7 projects contained printed elements on a building scale. 2 projects (including the research project) were on a product scale.

Materials
Printing in the built environment can be done in a variety of materials like steel, concrete, plastics, and

even stone. For the printed objects, one type of material is used for the printed objects. This can be explained by the fact that these materials have their own technological best practices. Objects with multiple materials printed in them cannot be found (yet) in practice. The exact properties of the materials often constitute an unknown in the project, meaning additional testing is required to obtain knowledge on material characteristics and mechanical properties.

Printing style
Where traditionally mere "inside the box" printing systems were available, 4 out of 7 cases adhere to the "outside the box" principle. This overcomes the obstacle that the printed objects have to be smaller than the printing system that is used. This enables easier transportation of the printing systems to construction sites and reduces mobilization time when a printer is installed on a new location.

Location of fabrication
5 out of 7 projects fabricated the 3D printed elements off site. For two projects, the fabrication of the elements was done on site. This confirms the existing preferred method of producing 3D printed elements at an off site location with a controlled environment.

Printed elements
Before going into detail on the type of elements that were printed in the project, findings show it is important to make a distinction between two main approaches. The first approach is to 3D print a small number of components in the overall project (valid for the printing components scenario). 5 out of 7 cases fall into this category. The second approach is to 3D print the majority of the structure (the 3D printing buildings scenario). 2 out of 7 cases fall into this category. The impact of both approaches on governance is assessed in chapter 7 on two levels: the product governance (of the printed component), and the overall project governance including the interfaces.

Different cases printed different types of elements. In 2 out of 7 cases ornaments (stuff) were printed. In 1 case, inner walls (space) were printed. In 3 out of 7 cases, the façade (skin) was printed. In 3 out of 7 cases, the printed components included structural elements.

Employed Technology
Different types of printing systems and printing technologies can be identified. These systems are often based on existing technologies and then developed to make them more suitable for construction. For example, for 5 out of 7 cases "inside the box" suspended systems were replaced by industrial robots from Acotech, KUKA and ABB.

Motivation for applying 3D printing
The first additional characteristic relates to the motivation to use 3D printing. Namely, whether printing was used as a means to achieve project objectives, or if it was used as a goal in itself. For the majority of the cases (4 out of 7), printing could be considered as a goal in itself. This means that the client (or initiator) listed it as a requirement. This confirms that 3D printing is currently at the early adopter phase, where (visionary) organizations aim to create proof of concepts and develop business cases that could potentially result in a later competitive advantage. For the remaining cases 3D printing can be considered as a means, with the Great Pagoda being the most clear example where it was more cost efficient to 3D print the element. Here feasibility was first studied by the client before the decision to use 3D printing was made.

Sources of (additional) uncertainty
3D printing is a new construction technology and introduces additional uncertainty in a construction project. This has an influence on project governance, because additional uncertainty requires additional activities to reduce or resolve it. Not all projects have the same degree of uncertainty before starting the project, as they differ in amount of experience they have gained with 3D printing. To give a measurement of this uncertainty, the sources of it can be identified:

- Materials

- Software
- Printing System
- Structural verification strategy
- Process maturity (capability maturity level)

Uncertainties in materials, software and the printing system/robotics are related to the technology development, of which the maturity can have different degrees. 6 out of 7 projects required some form of technology development. This can vary from small calibrations to the printing system to verifying and testing the materials that are used. The structural verification strategy was frequently listed as a key uncertainty. Finally, since most clients and project coordinators use 3D printing for the first time, they are not yet aware of what activities are required and how responsibility should be best allocated. There processes are therefore generally not mature (measured by the capability maturity model). This research will contribute to reducing this uncertainty in projects, making it more feasible to apply 3D printing.

6.8.2 Organizations, roles and responsibilities

A number of new and existing organizations can be identified. These organizations can fulfil multiple roles, and even take over roles (like design and engineering) that are traditionally allocated to other organizations. The distribution of roles is inconsistent between projects. The value chain of 3D printing in construction projects can therefore be described as fluid. Another way to describe it is that it is unestablished, as a result of a low level of technological maturity.

Rather than stating the organizations that can be recognized, it would be more accurate to state the roles that are present when 3D printing is applied in a construction project. The organizations that take on these roles in projects originate from either the traditional construction industry (like DUS acquiring and developing a printing system, becoming the service provider), are new to the industry (like MX3D, XtreeE and CyBe), or come from other industries (like 3D systems). The increased fluidity between industry boundaries is confirmed by Rogers to be a consequence of the digital transformation. (D. Rogers, 2016)

The roles that were identified can be observed on both governance levels, namely on a project level and component level. Additionally, the 3D printed component has several sub processes which can be defined as subcomponent level. Figure 42 describes all existing and new roles that have responsibilities related to the 3D printed component. Existing roles are normally already present in construction project, but their responsibilities increase as a result of applying 3D printing. New roles are normally not present in construction projects, and deliver a new type of value to the project. The responsibilities of the specific roles are stated above the specific role. Some roles have responsibilities on different levels, for example the engineer who is responsible for both integrating the component in the overall engineering design, as well as the structural verification of the component. Figure 42 positions the project manager as the clients representative.

A more detailed description of these roles is presented in tables 10 to 14 following figure 42, by stating a role description, when they were generally involved, what their responsibilities are related to the 3D printed component, and which organizations took on these roles in the projects. A dominant role on the component level is that of the 3D printing service provider, who often takes responsibility for the whole process (technology development, design, engineering, manufacturing) for the 3D printed components.

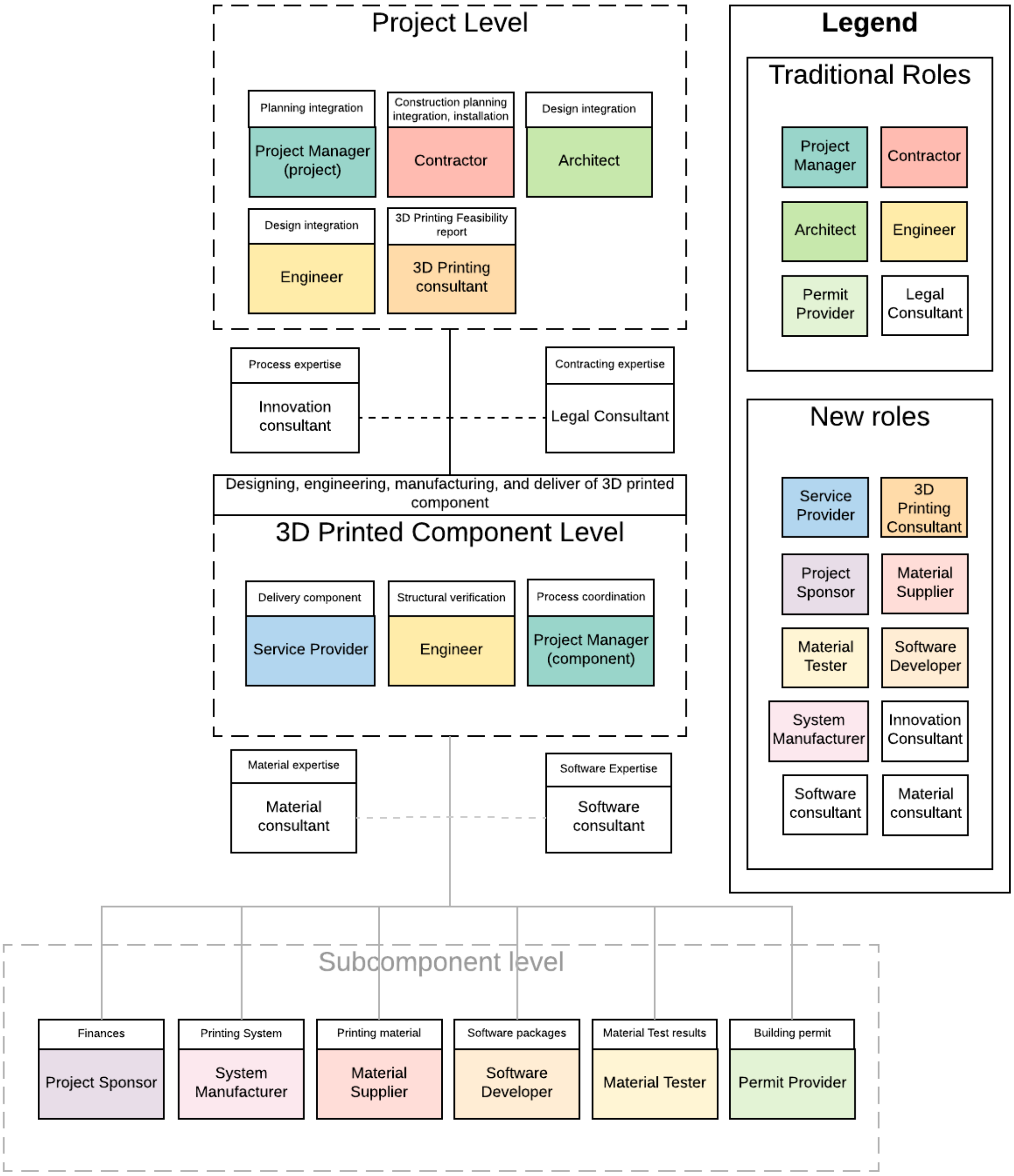


FIGURE 50 ROLES AND RESPONSIBILITIES FOR A PROJECT IN WHICH 3D PRINTING IS APPLIED ON A PROJECT, COMPONENT AND SUBCOMPONENT LEVEL

Role	Definition	Involved in phases:	Responsibility	Type of Organization
Architect	Overall designer of the project.	VO, DO, TO, Construction	Defining the general shape of the 3D printed component Design integration 3D printed element with overall project.	Architectural firms (DUS, Marc Dalibard, TFF, Universe Architecture)
Contractor	Builder of the project as designed by the architect and engineer	UO, Construction	Interface Management between 3D printed objects and overall project on site	Contractors (BAM, AD Concept)
Engineer	Overall technical designer of the project	VO, DO, TO, Construction	Design integration 3D printed element with engineering design	Engineering firms
3DP consultant	Provides consultancy services related to 3D printing feasibility	Feasibility	Delivery feasibility report	Engineering firm (Arup)

TABLE 9 ROLES ON A PROJECT LEVEL

New Role	Definition	Involved in phases:	Responsibility	Type of Organization
Service providers	Deliver finished 3D printed elements for a construction project.	Technology development, Design, Manufacture, Fabrication	Technology development (design of printed element) Engineering of 3D printed element Manufacture of 3D printed element	3D printing startups Construction Industry (Aectual, XTreeE, CyBe, MX3D) (3D printing) Manufacturers (3D Systems)
Project Engineer	Technical designer of the project, providing technical expertise to the architects design.	Design, Manufacture	Structural verification (strategy) 3D printed objects	Engineering firms (Arup, Witteveen & Bos, Artelia)
Project Manager	Coordinates the process of the 3D printed component	All component phases	Coordinating the 3D printed component process	Innovation consultant (Revelating), Service providers (MX3D, XtreeE, CyBe), Architects (Universe architecture), Clients (Royal Historic Palaces)

TABLE 10 ROLES ON A COMPONENT LEVEL

New Role	Definition	Involved in phases:	Responsibility	Type of Organization
System manufacturer	Manufacture and supply the 3D printing systems to the service providers (which are then often developed further internally)	Technology Development	Supply (raw) printing systems to service providers	Robotics Industry (ABB, KUKA, Acotech) 3D printing industry (3D Systems)
Software developer	Develop and supply software required for the printing systems, and provide related expertise	Technology development	Supply software packages for 3D printed components	Autodesk (Dynamo, Revit), Mcneel & associates (Rhino & GH)
Material supplier	Develop, produce and supply material for 3D printers.	Technology Development, Manufacture	Supply printing material to service providers	Traditional construction material suppliers (LaFarge) 3D Printing industry material suppliers
Material tester	Identify material properties of 3D printed elements through laboratory tests	Technology Development	Provision of material properties (E Moduli, Compressive and tensile stress).	Universities (TU Delft, TU/E), Research laboratories (DCL)
Permit provider	The building permit providing authority, which is involved to obtain what alternative requirements could be fulfilled to obtain a permit.	Design, Structural verification	Provide the building permit	Municipalities
Project Sponsors	Contribute financially and in kind to the technology development and overall project.	All project phases	Providing financial resources	IT-firms (Autodesk) Robotic manufacturers (ABB, Acotech) Contractors (BAM) Architects (DUS)

TABLE 11 ROLES ON A SUBCOMPONENT LEVEL

New Role	Definition	Involved in phases:	Responsibility	Type of Organization
Legal consultant	Provide expertise on new types of collaborative contracts between project participants	Product Definition & Partner Selection	This expert is consulted, but does not have a direct responsibility	Law firms (Lexence Advocaten)
Innovation consultant	Provide expertise on processes to apply 3D printing	Feasibility, product definition	This expert is consulted, but does not have a direct responsibility	Revelating
Software consultant	Provide expertise on the software required to develop the printing system	Technology Development	This expert is consulted, but does not have a direct responsibility	Autodesk, ABB
Material consultant	Provide expertise on material development	Technology Development	This expert is consulted, but does not have a direct responsibility	AEB

TABLE 12 SPECIALIST CONSULTANTS

6.8.3 Phases

A general distinction can be made between the phases for the 3D printed components (product governance) and the phases of the overall project (project governance). All cases applied 3D printed components, rather than printing a full building. A distinction should therefore be made between the phases of the overall project and the phases of the 3D printed component. The degree of interaction between the phases of the project and the phases of the 3D printed components show different degrees of interaction, varying from complete separation (R&Drone laboratory) to complete integration (Vergaderfabriek).

Also, though the phases seem to have a chronological linear fashion, the cases revealed a different sequencing of these phases, and also iterations between them. This can be traced back to the existing uncertainty related to the application of 3D printed components, and the low level of maturity of its processes (see 4.6.2 on capability maturity models).

The phases of the 3D printed components (those of the overall project can be found in paragraph 5.2.1) are as follows:

- Technology development
- Project definition
- Partner selection
- Design
- Manufacture

For the Great Pagoda project, a feasibility phase could also be identified. It is likely that this is correlated with the fact that printing here was a means to an end instead of an end in itself. Feasibility therefore had to be studied to verify whether 3D printing could be competitive to traditional manufacturing methods (which it was).

Technology development is a phase in which the technology for (construction) 3D printing is developed. This can relate to the material, the software, or the systems that are used. In traditional projects, this technology is fully developed and does not require additional activities throughout the project. Because the 3D printing technology has not yet matured however, it requires additional work to be done in order for it to be sufficiently mature to apply in the project. Sometimes a specific phase is allocated to one (or multiple) of the domains (material, software, printing system) to be developed prior to the start of the project. Often though the activities required for the technology development are spread out over the other project phases.

The duration of this phase depends on the experience of the organization and maturity of the technology to be used in the project. This is strongly related to the degree technological uncertainty (see 6.8.1), which varies from very high (Landscape House), to very low (The Great Pagoda).

Project Definition is the phase in which the project is selected and defined, and therefore includes the definition of the 3D printed component. It answers the question: what elements do we want to build? In the studied cases, often the project definition phase included a conceptual design, of which parts would have to be printed.

Partner selection is the phase where the partners that will realize the project are selected. It consists of identifying what capabilities are required and which organizations have these capabilities. The organizations are then approached and contracts are made.

Design is the phase in which the design is made for the 3D printed component. This is always done through a parametric virtual 3D model, most often in Rhino and Grasshopper (existing software packages capable of creating complex geometries). It has to fulfill both architectural and manufacturing requirements, as the finished product of the design phase is a file that can be directly printed. Interaction was observed between the design of the printed component and overall project with varying degrees of intensity.

Manufacture is the phase in which the printed element is manufactured, assembled, transported and installed on site, and in some instances structurally verified. The degree in which these activities are required depends on project characteristics, including element size, location of production and structural verification strategy. Again, new interfaces were observed between the printed components and overall project. with the overall project elements and actors on site.

Feasibility is a phase in which the competitiveness of 3D printing relative to traditional manufacturing methods is studied. The risks and opportunities are identified, on which the technology can be compared to traditional manufacturing methods and a more informed decision on whether to use 3D printing can be made by the client.

This phase was only identified in the Great Pagoda project, but is likely to become an increasingly important aspect as the technology matures. At the moment the value to cost ratio of applying 3D printing does not seem to be competitive with traditional manufacturing methods, but as the technology matures this ratio will come closer to the point where it is competitive with traditional manufacturing methods. At this point it is likely that clients will request services in order to decide whether 3D printing could add value to their project, meaning a feasibility phase is likely to occur more frequently.

6.8.4 Activities

The detailed activities for the individual phases are on a high level of detail and therefore not elaborated in this paragraph. Best practices were extracted and presented in paragraph 8.3. In paragraph 8.4, detailed activities that were used for the designed governance structure are elaborated.

6.8.5 Challenges

The identified challenges in literature were largely confirmed. The cases showed a variety of approaches to deal with these challenges, which are presented in this chapter. This will serve as input for the designed governance structure in chapter 8.

Unknown material properties
Little is known on the material properties of printed components. The products created by 3D printing can have anisotropic, heterogeneous properties, which are influenced by the printing technology and manufacturing parameters that are used. The relation between these manufacturing parameters and printed products however, is often not known. The unknown material properties results in additional uncertainty and activities in the project.

Different ways are found to deal with this issue. At an initial stage, laboratory tests can be done on printed samples (with specific manufacturing parameters), giving an indication on the mechanical performance of material. During the construction stage, the manufacturing process can then be monitored ensure these laboratory tests are still valid for a new product. Another approach is to use negative printing: 3D printing a mold and casting in a traditional material (with known properties).

Acquisition of building permit
Another challenge is the acquisition of a building permit, which is required for construction to commence. It is closely related to the challenge above, as traditional building codes cannot be applied when detailed material properties are unknown.

Several approaches were recognized to deal with this issue. The first approach for concrete is to print the contour, place reinforcement, and cast in conventional concrete (for which properties are known). The second approach for concrete is to print the contour of the element and casting UHPC (with known properties) in it. The third (planned) approach for steel is to verify the manufacturing process and perform tests on the final product. This is already done in the aviation industry (Vincent, 2017), and a topic of ongoing research within Arup.

Cases also revealed organizational and geographical solutions to deal with this challenge. For the R&Drone laboratory, the building was constructed in Dubai, where the requirements for a building permit are lower than in Europe. Creative thinking and problem solving here is done more often during construction. Combining this with their vision of printing 25% of newly constructed buildings in 2030, this makes it an attractive location for the first projects in which 3D printing is applied. An organizational solution was recognized in the Vergaderfabriek project, where the permit provider was involved at an early stage, to identify potential alternative requirements to be satisfied in order for the building permit to be granted.

High Cost
The costs of using 3D printing are (currently) higher than using conventional fabrication methods. This is not only due to the fact that the cost of printing itself is high, but also the time and energy spent on developing the technology and reducing the uncertainties. These drive up the price of applying 3D printing in a project, making it less competitive with traditional manufacturing methods.

This challenge is dealt with by attracting investors with potential business cases in 3D printing. The organizations who invest in the projects have a variety of backgrounds, indicating that different types of business cases could emerge when 3D printing becomes more actively applied. Software firms (Autodesk) see a potential for increased application of algorithmic design, in which a computer generates design alternatives , potentially in an evolutionary way (Autodesk, 2017a). Robotic manufacturers (ABB, KUKA, Acotech) see a potential new application for their robots on the construction site. Contractors (BAM, Vinci, Heijmans) see an opportunity to reduce cost (as often lumpsum contracts are applied and cost savings result in direct profit for them). Architectural firms (DUS) are inspired by the increased design freedom it could offer. Waste processing plants (AEB) see an opportunity to add value to valueless materials (waste), by making them suitable for construction of newly built objects.

Furthermore, it should be noted that though 3D printing is currently more expensive than traditional manufacturing methods, the new type of freeform structures can have significant additional value to clients. This makes the comparison in value to cost of both construction technologies difficult to compare. The cases seem to indicate that currently customers are not willing to pay the additional associated cost for this additional value, but this might change as soon as more inspiring examples are delivered to the public.

Construction's conservative, fragmented culture.
3D printing in construction is a very innovative technology for a traditionally conservative industry, that requires behavioral change from its organizations. Existing processes, business models and skills and capabilities of traditional organizations are all oriented towards standard practice, and have been optimized for decades. These are not easily changed towards a freeform design culture. People will need training and education, but also inspiration and examples to become more aware of the opportunities and limitations of the technology. What makes this process additionally challenging is that a construction project often contains a lot of organizations. These all have to support the innovation and learn how to utilize it.

One case dealt with this issue by hiring an innovation consultant, which aimed at learning the organizations to think outside their traditional paradigms.

Low level of technological maturity
Freeform construction is often stated as an opportunity because it allows for functional optimization, resulting in less material usage and weight reduction. There are however technological limitations to utilize the benefits freeform construction presents. Firstly, the existing design software does not allow for the type of functional optimization needed to fully utilize the benefits enabled by freeform production. During the 3D printing conference 2017 in Amsterdam Dr Wits stated that "*where normally manufacturing is running behind on designers, currently it is the opposite*". The complexity that can be currently manufactured is more advanced than what designers can take advantage of. Secondly, as the scale of the printed elements increases, the material imposes limitations on the inclination angle that can be achieved.

The solution for these problems is more research on the technology. As 3D printing is currently an active topic of research, this challenge is expected to reduce over time. It is something that cannot be influenced by a client aiming to implement 3D printing, besides the selection of the right partners with experience in printing.

6.8.6 Future improvements

Interviewees gave a wide variety of answers in what could have been improved and in what they see as future opportunities. These can be divided in ways to improve the governance they applied, and what future opportunities are present for 3D printing.

Improvements existing governance
An interesting comment was that given the amount of uncertainty in the project, the process was well set up. In a next project however, this uncertainty will be reduced and the project will be more efficient.

Three other suggestions for further improvement indicate the additional difficulty in applying innovation in a construction project rather than an organization. The comments were:

- Having an in-house printer available to speed up the technology development process
- A stable project team working from start to completion of the project.
- A client with a clear vision and frame's is key to realize these type of projects
- Having production facilities at the same location to simplify logistics

These aspects are more present in organizations than in a fragmented construction project.

Future opportunities for 3D printing

Key opportunities mentioned by the interviewees include:

- Closer collaboration and more knowledge exchange between fragmented disciplines in a construction project
- Reducing development time of projects. Design aided by a computer can increasing speed of feedback loops and reducing overall design time.
- Larger business cases. The parametric model that was made for the R&Drone Laboratory can easily be modified for similar type of projects. Because design principles are already integrated in these models, 80% of the design work is already done, making it more cost effective once more similar buildings are designed. This might seem like the conventional mass production way of thinking, but the key difference is that the buildings can still be customized on several domains, including orientation, floor plans, total surface area, and contour lines.

6.8.7 Governance Domains

The observed governance domains for the 7 case studies are presented in figure 51.

Case Study	Governance construction project	Governance product design	Governance innovation
3D-Printing in the Circular City		X	X
De Vergaderfabriek		X	X
R&Drone Laboratory	X	X	X
MX3D Bridge		X	X
The Great Pagoda	X	X	
Post Aix-en-Provence School	X	X	X
Landscape House	X	X	X

FIGURE 51 GOVERNANCE DOMAINS OBSERVED IN ALL CASE STUDIES

Four case studies that implied the first scenario in which a number of 3D printed components is applied are the R&Drone laboratory, the Great Pagoda, the Post Aix-en-Provence School, and the Landscape house. Two case studies that implied the second scenario in which the majority of a building is 3D printed are the Vergaderfabriek and the MX3D Bridge. The "3D Printing in the circular city project" produced a 3D printed component that was not integrated in an overall construction project. This means that the governance domains observed can be generalized for all three scenario's. The governance domains observed for the three scenarios are described in figure 52.

Project type	Governance construction project	Governance product design	Governance innovation
3D Printed Component		X	X
Construction project in which 3D printed components are applied	X	X	X
Construction project where majority of its components is 3D printed		X	X

FIGURE 52 GOVERNANCE DOMAINS FOR FUTURE DEVELOPMENT SCENARIOS

Several conclusions can be drawn from this analysis.

There is not one best practice to the governance of construction projects in which 3D printing is applied. Rather, it should be a combination of different governance domains. The way in which these are best combined is described in chapter 8.

The construction projects in which a number of 3D printed components is applied show elements of the governance domains construction project, product design and innovation. If the 3D printing technology is mature however, it only shows governance elements from product design and construction projects.

Governance of construction projects in which the majority of its component is 3D printed include elements of the domains product design and innovation, not construction. This means that the traditional construction project governance is not valid for these type of projects. Rather, the main process is best described by a governance model for product design.

7 Current differences between governance of a project in which 3D printing is applied and a traditional construction project

This chapter will present the differences between the governance of a project in which 3D printing is applied and the governance of a traditional project. An high level overview of these differences is presented in paragraph 7.1. Paragraph 7.2 then presents what changes to the traditional governance are required on an operational level. Paragraph 7.3 presents additional opportunities which can be utilized when designing the two governance structures in chapter 8 and 9.

Research Question	Answered in
(2) What are the current differences between the governance of a project in which 3D printing is applied and a conventional project?	7.1, 7.2

7.1 From traditional project governance towards product design and innovation

When comparing the observed governance of the case studies to that of a traditional construction project, it can be observed that besides the governance of a traditional construction project, governance domains of product design and innovation are also encountered, with the product design domain being valid for the 3D printed component.

The overall impact of applying 3D printing therefore, is that a transition from traditional project governance towards the governance for product design is adopted. When a small number of 3D printed components is applied, this different governance approach will have a minor impact, since it has a minor role in the traditionally governed construction project. As soon as 3D printing is used for the majority of a building however, a product design model becomes dominant for the project and the traditional governance of construction projects is no longer present.

It should be noted that in the future, the governance domain innovation is expected to reduce as the technology and related processes mature. The overall differences in governance domains that can be observed in a project when comparing the two scenario (now and in the future) to a traditional construction project are presented in figure 53.

Project type	Governance construction project	Governance product design	Governance innovation
Traditional construction project	X	(X)	
3D Printed Component		X	X
Construction project with 3D printed component	X	X	X
Construction project where majority of components is 3D printed		X	X

FIGURE 53 CURRENT IMPACT OF 3D PRINTING ON PROJECT GOVERNANCE

Project type	Governance construction project	Governance product design	Governance innovation
Traditional construction project	X	X	
3D Printed Component		X	
Construction project with 3D printed component	X	X	
Construction project where majority of components is 3D printed		X	

FUTURE IMPACT OF 3D PRINTING ON PROJECT GOVERNANCE

When looking at the first scenario (highlighted in yellow on the left in figure 53) in which a number of 3D printed components is applied in a construction project, the governance of the 3D printed component is characterized by a combination of product design and innovation.

7.2 Resulting impact on project governance

The application of 3D printing in a construction project results in several concrete implications for its overall governance:

- Central role for manufacturer
- Standard contracts are not applicable
- Increased uncertainty and risk
- Alternative building permit procedure
- New skills for project stakeholders
- Traditional design phases are not applicable
- Additional Information System

These differences are based on analysis of the observed governance in the case studies. In this paragraph, each difference is elaborated, by listing why this difference occurs and how it should be dealt with. This last aspect is based on analysis and observations from case studies, and occasionally further elaborated in the design governance structure in chapter 8.

Central role of the manufacturer
Where normally the manufacturer is at the bottom of the hierarchy and involved in a very late stage of the project, he now gets a central role in the design process. This is because he provides an essential type of expertise to the design process, the manufacturing possibilities and limitations. Since this knowledge is incorporated at an early stage of the design process, he becomes a part of the early stages of the design process. Additionally, the manufacturer can provide essential input with regard to the associated risks which are defined in an early stage of the 3D printed component's development process.

To deal with this difference, the manufacturer should be involved at an early stage and the project team should actively collaborate with him, rather than outsource the work. By collaborating, the additional risk caused by applying 3D printing can be better mitigated (or utilized), and better insight can be gained on the interfaces to the overall project. This active collaboration with the manufacturer was found in the all of the case studies, with the exception of the R&Drone laboratory. Here, responsibility for the 3D printed component was outsourced to a service provider (who outsourced it to another service provider). No communication existed between the service provider doing the work and the overall contractor. This resulted in a large misalignment in the overall planning of the 3D printed component and overall project. Several legal proceedings and a significant time delay for the project followed.

Standard contracts are not applicable
The standard Dutch contracts (DNR + UAC) are not suitable for the 3D printed component. Close collaboration occurs between all disciplines, which provide their input to the same 3D model and work together in an iterative fashion. Due to this close collaboration, responsibilities for designing, engineering and manufacturing start to become more dynamic and context dependent, since everyone is contributing to the final output at multiple points in time. Splitting up the responsibilities for design, engineering and manufacturing would result in either a model which cannot be manufactured, or a model which is not functional. Additionally, the responsibilities of the manufacturer increase (he is contributing to the design process), meaning his contract towards the project becomes more than merely a purchase order to manufacture a certain amount of elements at a certain price.

Another point to take into account is related to the rights of the organizations contributing to the development of the 3D printed component, like Intellectual Property Rights (IPR) and confidentiality of information. Due to a more co-developed model, actors might object to the architect becoming owner of the model. Confidentiality of information could become an issue since the whole process becomes more transparent. It is a highly iterative which means organizations get more insight in the added value and knowledge of their competitors. Though these considerations were not found in the case studies, they are expected to become relevant when 3D printing is applied on a larger scale in a project.

To deal with this issue, a new type of contract between project team and manufacturer is required, which is more collaborative and incorporates the increased responsibilities of the manufacturer. Secondly, it is best to apply an integrated contract for the overall project. The required collaboration and holistic approach towards the 3D printing development process is not just between design and manufacturing, but also between all the disciplines within the design phase (project manager, architect, engineer, contractor). If these actors have a shared responsibility for the overall project, it becomes easier to facilitate the required collaboration. The (IP) rights of the organizations contributing to the development of the 3D printed component should be discussed at an early stage of the project, resulting in clear agreements on who is entitled to what.

Increased uncertainty and risk
Several elements of applying 3D printing in a project lead to additional uncertainty and risk regarding to schedule and cost of the 3D printed component. These can influence the overall project both positively and negatively. 3D printing technology might not be fully mature before starting the project, meaning it requires technology development to be done during the project where normally this is not the case. Secondly, iterations occur between the phases which makes the point where it is completed more uncertain (the design process might take longer, but can also go a lot faster than originally anticipated). The building permit acquisition procedure is an additional risk for the project, since uncertified manufacturing technologies are used. Project stakeholders are new to applying the technology and its related design process, meaning the integration of 3D printing in the overall project might result in problems or additional training.

This means that risk management becomes increases in importance. The mitigation (or utilization) of the most important risks are specified in paragraph 8.3, which state the best practices observed in the case studies. A positive risk for the contractor that is was not found in the case studies is the increased flexibility in delivery date of the component. Since the 3D printed file can be directly manufactured from a digital model and the process is fully automated, it does not require any physical inventory and can be delivered "on demand". This makes it easier for contractors to apply "just in time delivery".

Alternative building permit acquisition procedure
The 3D printed component requires a different procedure to obtain a building permit. This is because the manufacturing process of the technology is not yet certified, meaning the exact material properties of the resulting components are unknown. This means that the traditional codes and requirements for a building permit cannot be used and an alternative procedure is required.

To increase changes of obtaining a building permit, the municipality (authority granting the permit) should be involved at an early stage to agree on alternative requirements for the grant of the building permit. Potential procedures are discussed in paragraph 8.3. Secondly, responsibility for obtaining a building permit should be allocated to the lead project engineer or project manager, who should develop a structural verification process in collaboration with the municipality.

New skills for project stakeholders
Procedures for designing, engineering and manufacturing a 3D printed component are different than that of a traditional design process. New skills are therefore required from the project manager, architect, engineer, and contractor. The project manager must acquire additional skills on the management of a product design process and agile practices, and utilize a fit for purpose approach for management of the overall project. He should also be more flexible in the management of the overall project and deal with changing circumstances (to deal with the unknown unknowns in the project). The architect or engineer should learn how to design (and utilize) freeform components, and deal with its physical interfaces to the

overall design. (these are discussed in the paragraph 8.4.4). Contractors should learn how to integrate (or utilize) the flexible delivery date of the component(s) in their planning for construction, and their construction workers need knowledge on how to install and assemble 3D printed components on site.

During a project kickoff meeting, the responsibilities of each of these parties related to the 3D printed component should be specified (utilizing a RASCI matrix), and an inquiry should be made on what knowledge each actor still has to develop. Based on this, time should be reserved for education and development of associated skills. As soon as teams have more experience with applying 3D printing, this aspect reduces in importance.

Traditional design phases are not applicable
The traditional Dutch design phases preliminary design (VO), detailed design (DO), technical design (TO), work planning (UO) and execution VO, DO, DO, TO, UO and execution are not applicable to the 3D printed component. These phases assume a linear development with standardized deliverables containing 2D drawings and technical documentation which increases in detail with every design step. The development process of a 3D printed component is very different. It firstly does not have 2D drawings as deliverables, but 3D virtual models. These require little interpretation and can be iterated fast between the disciplines in design and manufacturing. Secondly, progression is exponential, rather than linear. Developing the initial strategy and obtaining all relevant input from design disciplines requires a lot of time, meaning the amount of deliverables at an early stage of the development process is very small. The only real deliverable is when the virtual and physical 3D model are finished.

Progress of the 3D printed component has to be measured and communicated in a different fashion. An example from a digitized design process in Arup is to explain the content of what is being done to the higher management in the project, so they understand what is going on rather than only looking at output. (Fysion & Clipsom, 2017)

Additional Information System
The information system used for a 3D printed component, consists of communication of 3D models. For a traditional project, communication is done in 2D drawings. Emphasis should be placed on how to align these different information systems to make sure that the physical interfaces between the 3D printed component(s) and the overall project are taken care of.

The ideal way to deal with this issue is to communicate in 3D models for the overall project, by applying BIM. If this is not done, responsibility should be allocated to individuals that will ensure that the physical interfaces between component and project are taken care of.

7.3 Additional opportunities

The previous paragraph primarily oriented towards the additional risks that 3D printing causes when compared to a traditional construction project. Applying the technology however also offers several opportunities for the project:

- Reduced lead time
- Increased transparency
- Flexible delivery date
- Flexible for changing requirements
- Complexity reduction
- Simplification site logistics

These opportunities are a translation from the generic opportunities in literature to construction project, and are used as input for the designed governance structures in chapter 8.

Reduced lead time
The fact that project actors work iteratively and can rapidly communicate in the same 3D models can

reduce the lead time of the 3D printed component. This means that the completion date of the virtual 3D model can happen both sooner and later than originally anticipated.

Increased transparency
In the process of designing a 3D printed model, actors collaborate closely and work iteratively. This results in increased transparency and mutual understanding between each discipline, who can develop a more holistic perspective on the project. This is normally not possible due to the fragmented nature of the design process. This might have a positive effect on the amount of learning and collaboration in the overall project, leading to more satisfaction in project teams.

Flexible delivery date
3D printed components can be produced on demand and do not require inventory, because the file is stored digitally and can be manufactured in an automated fashion at the push of a button. This makes it easier to apply "Just in time delivery" for manufacturers, who can supply the components at the exact point in time it is needed, without the need for large inventories.

Flexibility for changing requirements
A change in the design of a component is normally not easy to integrate in the overall project, and can go accompanied with a change in manufacturing technology, manufacturing settings and therefore a different supplier. When applying 3D printing, changing requirements can be captured within the same manufacturing technology, meaning the project team does not have to change the supplier. This means that changes can be more easily incorporated, also in a late stage of the design (or execution).

Complexity reduction
Traditional buildings consist of a large variety of different components (and related suppliers), and a large amount of steps between the initial design and actual manufacturing. With 3D printing monolithic pieces can be created which would normally consist of a lot of different components. This reduces the total number of components and suppliers in a project. The amount of steps between design and manufacturing is also reduced, so that production is very close to design. This makes the process easier to manage.

Simplification site logistics
3D printing can greatly simplify site logistics. The reduction of components and suppliers means less people are required on site. Waste processing becomes less of an issue, since 3D printed can make components without any waste. If on-site printing is used, transportation requirements do not have to be taken into account in the construction, meaning potentially large objects can be made in area's which are difficult to access. The flexibility of the delivery date allows for changes to be more quickly incorporated.

8 Project governance structure for projects in which 3D printed components are applied

This chapter presents the designed governance structure for the first scenario in which a number of 3D printed components is applied in a construction project. Starting points for the project governance structure are first presented in paragraph 8,1. A high level description of the governance of the project is then presented in paragraph 8.2. Best practices extracted from the case studies (and validated in literature) are presented in paragraph 8.3. These provide concrete activities to utilize 3D printing opportunities and deal with the challenges observed in the case studies and literature. Paragraph 8.4 then presents an operationalization of the high level description into the individual governance elements phases, roles, activities, responsibilities and interfaces.

Sub questions	Answered in
(3) What is a potential governance for a project in which 3D printing components are applied?	Paragraph 8.2-8.4

8.1 Starting points

The governance structure designed in this chapter is valid for the first scenario in which a number of 3D printed components is applied in a current construction project. It is made in a generic way so that it is valid for all project characteristics identified in paragraph 4.4. For two of these characteristics however, an initial assumption is made because they are too differentiating to incorporate in a generic governance structure.

These characteristics are the fabrication location (off site) and the motivation for using 3D printing (it is used as a means to achieve project objectives, rather than a design requirement). To remind the reader of the scope of this research, the component is newly built, has a freeform shape and is applied in a functional construction project. These characteristics are selected because they resemble the first projects in which 3D printing is expected to be applied. These characteristics are summarized in table 13.

For projects that do not align with these assumed characteristics, the governance structure presented in this chapter is still largely applicable, but might need modification. For example, when making a research project or artefact, structural certification procedures are not required.

Form Freedom	Purpose	Element Scale	Material	Printing Style	Location of production	Printed Elements	Employed Technology	Motivation for using	Sources of uncertainty
Rectilinear	Research	Product	Concrete	"Inside the box"	On Site	Stuff	FDM	**3DP as means**	Material
Freeform	Artefact	Building	Steel	"Outside the box"	**Off Site**	Space	SLS	3DP as goal in itself	Software
	Functional		Plastic (waste)			Structure	Binder Jetting		Printing System
			Nylon			Skin			Structural verification
			Stone			Services			Governance
						Site			

TABLE 13 STARTING POINTS FOR DESIGNED GOVERNANCE STRUCTURE

8.2 High level overview

If a project team decides to adopt 3D printing in their project, the project should be split into three layers:

- The overall construction project
- The 3D printed component
- The (immature) 3D printing technology

These layers are decoupled and treated as individual projects, each with a different governance approach. The layers and their accompanied governance domain and elements are presented in figure 54.

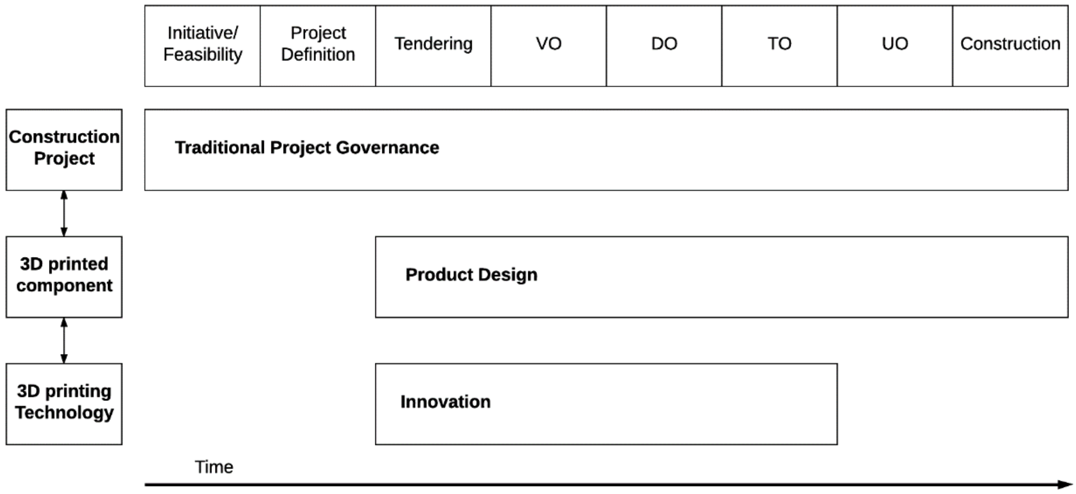


FIGURE 54 GOVERNANCE FOR A PROJECT IN WHICH A 3D PRINTED COMPONENTS IS APPLIED

The overall construction project has to be delivered through utilizing the governance of traditional construction projects. This structure is the most suitable for now because it has been optimized and the large variety of project organizations all have experience with them. An integrated (D&B) contract is chosen because it facilitates the integration between design and manufacture for the 3D printed component.

The 3D printed component has to be designed and manufactured utilizing the governance of product design, to facilitate the close collaboration between disciplines, iterations between design phases and active involvement of the manufacturer. This process starts as soon as a general description and requirements for the components can be formed, of which the earliest point is the tendering phase. Starting this process at an early stage reduces the chance that potential delays in the delivery date of the component influence the schedule of the overall project.[9]

If the 3D printing technology is not yet mature and requires additional development, the governance domain of innovation should be applied. This allows for more agility, room for experimentation and embraces the associated uncertainty.

8.3 Best practices

Several best practices are extracted from the researched case studies, which offer solutions to existing challenges and utilize the opportunities that 3D printing presents. A large portion of these best practices are validated in literature on innovation and product design.

[9] If the technology becomes more mature and the associated risks reduce, the process can also be started at a later stage

Decoupling of project layers
Decoupling the total project into individual layers makes the process more structured and creates accurate expectations for project managers on how they should change their approach when dealing with different layers in the project. If only the rigid stage gate process from traditional project governance would be used, there would be little flexibility which is needed for 3D printing and especially the development of its technology. If the whole project is managed in such a flexible way however, a project manager loses control over the project. A flexible "fit for purpose" governance approach is therefore more optimally suited to integrate the different approaches. This best practice is also proposed literature, in *"Management of innovation and product development"*. (Cantamessa & Francesca, 2016)

Adopting a product design approach for the 3D printed component
The adoption of a product design approach has several advantages:

1) It allows the manufacturer to be involved early in the design process

In a product design process, it is common for the manufacturer to be involved at an early stage in the design process, to collaborate with the designer on the possibilities and limitations imposed by manufacturing. Though the resources spent during these initial phases is low, the decisions at this early stage have a large impact on the final cost of the product (Cantamessa & Francesca, 2016). This means that by allowing all relevant disciplines to provide their expertise in an early phase of the design process, lifecycle cost of the product goes down. In the construction industry this principle is recognized but limited to early contractor involvement, not the manufacturers themselves.

2) It emphasizes active collaboration between all disciplines

Active collaboration is particularly important between the design and manufacturing disciplines, which enables the required holistic design process for 3D printing (Labonnote et al., 2016). Collaboration should be encouraged by new types of contracts, that emphasize partnering rather than hierarchical relationships between organizations. The collaborative contract found in the Vergaderfabriek is an example of this.

3) It allows for iterations between the design for manufacture and functional design

Iterations between design phases are expected and very common in product design and can speed up the design process. Hendriks (founder of CyBe), stated that the increased amount of feedback loops can result in a reduced lead time for the overall project, which he identifies as an opportunity for future projects. Frank Piller, a professor at the university in Aachen, stated during his speech at the 3D Printing Conference 2017 in Amsterdam that in more modern innovation approaches all phases are gone through simultaneously rather than sequentially, accelerating time to market of new products.

The management of these iterations can be done in two ways

- Developing two iterative activities in parallel and letting the involved people coordinating this overall process themselves. This is referred to as using concurrent engineering (Cantamessa & Francesca, 2016). In the higher level management these two activities are treated as one activity block.
- Decoupling the iterations cycles into sequential steps. In other words, rather than introducing a cyclic nature between A and B in the planning, it is split in A1-B1-A2-B2-A3 etc…. An assumptions has to be made then on the time required of the individual activities. (Cantamessa & Francesca, 2016)

4) It allows the usage of modern digital communication system between the disciplines

The digital nature of the design process should be facilitated by digital communication channels. The state of the art in product development is represented by Product Lifecycle Management (PLM) systems, (Cantamessa & Francesca, 2016) and seem to be similar to BIM approaches in the construction industry. This becomes particularly important when the 3D printed product consists of multiple individual parts which have to be assembled. A PLM system can ensure an integrated approach to make sure that there is one overarching integrated model that includes all relevant information.

A feasibility study prior to the decision of applying 3D printing
A feasibility study provides comprehensive information on the potential application area, the value and the associated risks. This should be done by comparing 3D printing technology to traditional manufacturing technologies in terms of value, cost and risk. It enables a more informed decision on whether or not to apply 3D printing, and creates an initial risk profile for the 3D printed component. This best practice was observed in the Great Pagoda project.

Specification of certainties and uncertainties in the product definition stage
During the product definition and partner selection stage, the certainties and uncertainties should be clearly specified. This creates a risk profile for the 3D printed component, and results in more accurate expectations regarding to expected delivery time and cost of the final product. Additionally, it provides awareness on the amount of technology development projects that can be expected in the project which can then be compared to the overall project planning.

Uncertainties should be categorized in project dependent and project independent uncertainties. Project independent uncertainties might be outsourced to researchers, while project dependent uncertainties should be resolved by the project team.

A point to be aware of here is the incentive for the service provider to overstate their promises, as they could view the project as a means to get paid for gaining valuable experience that they can use in developing and fine tuning their technology. An activity that can be helpful here is the cross referencing of information during the project definition phase, for which (independent) universities can be consulted. These best practice were observed in the Vergaderfabriek project.

Early development of a structural verification strategy
A key challenge mentioned in literature and observed in the case studies is the compliance with existing building codes and standards which are not yet present when 3D printing is applied. This is due the unknown material properties. The solution is a define a structural verification strategy at an early stage of the project. Two options can be considered: 3D printing a mold in which known materials are casted (meaning the traditional codes can be used), and a customized structural verification strategy for directly printed objects.

The latter option consists a high risk process which should be carefully managed by the project manager. Since there are no standards yet, safety will have to be demonstrated through a physical load test on a representative object, before it can be applied in the project. Such a test was recently conducted on a scaled model of a 3D printed bridge in Groningen. (Cement, 2017) Since codes do not specify what type of object would be "representative", the municipality providing the building permit should be involved at an early stage to discuss this. This increases the likelihood of the permit being granted at a later stage. Several activities can reduce the uncertainty in the outcome of this final test:

- Laboratory tests on smaller printed samples
- Providing the results to a structural engineering firm who can use it for structural calculations
- Tests during the manufacturing process

Because structures have to perform their function over their entire lifecycle, structural verification does not stop at the construction phase, but is a continuous activity throughout the life cycle of the project. Because no existing information exists on the long term performance of large 3D printed structures, sensors can be placed on the bridge to monitor its performance during the in-use stage. Engineering firms have experience with the relevant codes and requirements for structural safety, and should be involved in this process. This best practice was observed in the MX3D project.

Involvement of visionary organization (as client and/or project team)
The 3D printing technology and processes are currently rarely cost competitive with (optimized) traditional manufacturing technologies. However, there is a lot of interest in the future opportunities and applications of the technology. In projects, this can be utilized by involving visionary organizations willing to invest time and resources into development of the project. This concerns the client, but also the organizations that contribute to the product development process. They can gain experience and therefor form new business models in the future. This best practice was observed in nearly all case studies.

It is important to consider that these visionary organizations will have a motivation for participating that is broader than the objectives of the specific project. This could mean that they might demand additional activities in turn for their commitment. (Moore, 2014) It is therefore ideal to involve not more than one or a few visionary organizations, to ensure the same vision towards the project is held.

Staffing the project with technology enthusiasts
Though the construction industry is generally conservative, it is likely that there is a small group of people within the involved organizations that are passionate about innovation. Staffing the project with these technology enthusiasts ensures that they are committed and passionate towards its final delivery. In literature on innovation it is confirmed that rather than externally enforcing innovation to happen, it is better to facilitate the existing innovators within the company. (Cooper, 2015)

8.4 Operationalized Governance Structure

This paragraph presents an operationalization of the high level overview presented in paragraph 8.1. It incorporates the best practices described in the previous paragraph and utilizes the opportunities presented in paragraph 7.3. The operationalization is done by first visualizing the phases (8.4.1) and presenting the roles (8.4.2). Responsibilities and activities for each phase is presented through a visual diagram and a RASCI matrix (8.4.3). Interfaces between the three project layers are finally presented (8.4.4)

8.4.1 Phases

Figure 55 describes all phases in the project, which are divided into the layers construction project, 3D printed component and 3D printing technology.

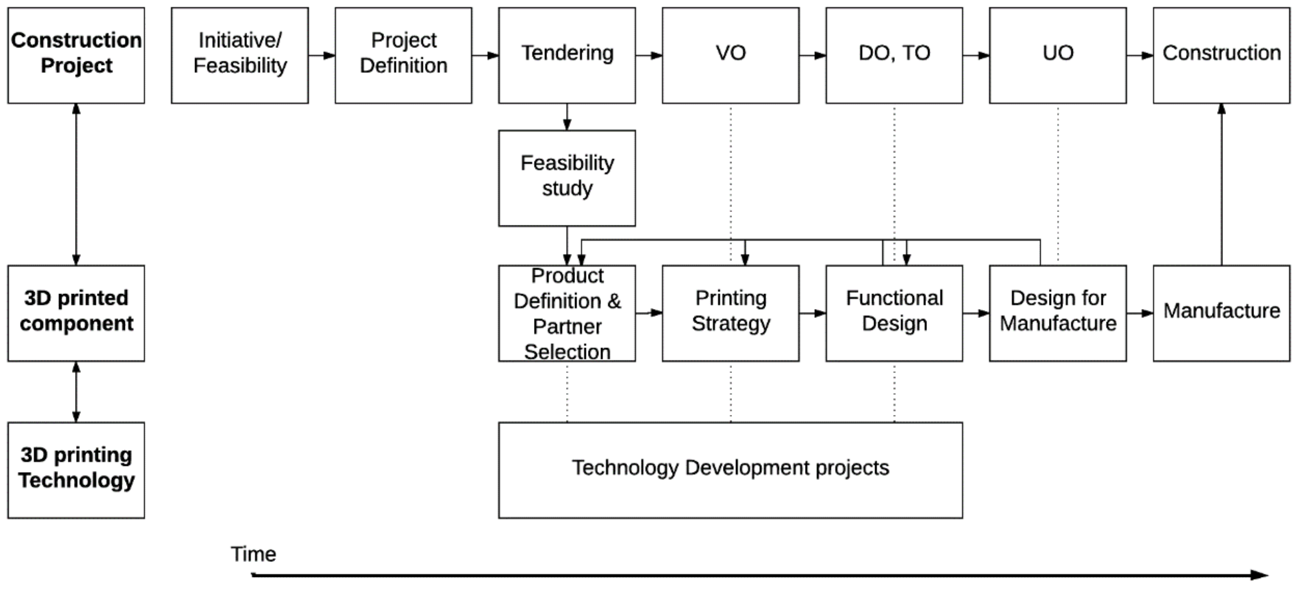


FIGURE 55 PHASES OF THE PROJECT IN WHICH 3D PRINTED COMPONENTS ARE APPLIED

The diagram assumes a D&B contract to facilitate an integrated approach towards the project delivery. The moment where 3D printing is introduced is best to be done as soon as a general description of the functionality can be formed. This is best done as early as possible, to leave room for the uncertainty and iterations for the 3D printed component. If the component is smaller and has a high technological maturity, the process can also be started later in the design (like DO or TO).

8.4.2 Roles

Tables 15 and 16 describe the roles that will be present in the project, including in which phases they are involved. The described roles are centered around the 3D printed component, with the architect responsible for the design integration in the overall project and the contractor responsible for work planning integration and assembly in the overall project. In table 16, the project manager acts as the clients representative. The client is therefore not stated as a separate role.

Traditional Roles	Abbreviation	Involved in phases:
Software developers	SD	Technology Development
Material supplier	MS	Technology Development, Manufacture
Project Sponsors	PS	Technology Development
Permit provider	PP	Printing Strategy, Design, Manufacture
Engineer	ENG	Technology Development, Printing Strategy, Functional Design, Manufacture
Architect	ARC	Feasibility, Product definition, VO, DO, TO
Contractor	CON	Design for Manufacture, UO & construction (work planning integration)
Project Manager	PM	All project phases

TABLE 15 TRADITIONAL ROLES WHEN APPLYING 3D PRINTED COMPONENTS

New Roles	Abbreviation	Involved in phases:
Service providers	SP	Technology Development, Product Definition & Partner selection, Design for Manufacture, Manufacture, Construction
System manufacturers	SM	Technology Development
3D printing consultant	3DPC	Feasibility
Material tester	MT	Technology Development
Material consultant (optional)	MC (o)	Technology Development
Innovation consultant (optional)	IC (o)	Technology Development, Printing Strategy
Legal consultant (optional)	LC (o)	Product Definition & Partner selection

TABLE 14 NEW ROLES WHEN APPLYING 3D PRINTED COMPONENTS

8.4.3 Responsibilities

This paragraph describes the deliverables, activities and responsibilities within the phases described in figure 56. The responsibilities are presented through a RASCI matrix. The role abbreviations in these matrices are presented in table 14 and 15. If not self-explanatory, activities are briefly explained.

A visualized representation demonstrates the relationships between the activities, and highlight which actors are responsible for the activity. This is done by giving the activity a color that corresponds to a specific role in the project, as indicated in figure 56.

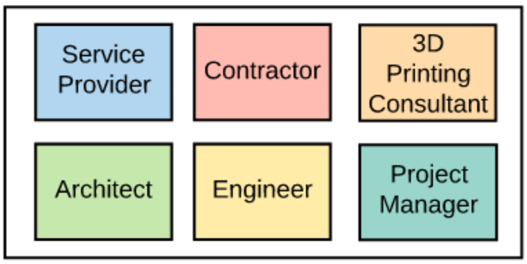


FIGURE 56 RESPONSIBILITY COLORS IN VISUALIZED DIAGRAMS

It should be noted that the exact activities might be different when the project has different characteristics than stated in paragraph 8.1. Also, the allocation of these responsibilities can be customized based on the unique requirements of the project and involved organizations.

Feasibility study
The goal of the feasibility study is to provide the information required to a high level description of what elements should be printed, and make an informed go/no go decision on whether to apply 3D printing for these elements. Activities are presented in figure 57, the corresponding RASCI matrix is presented in table 16.

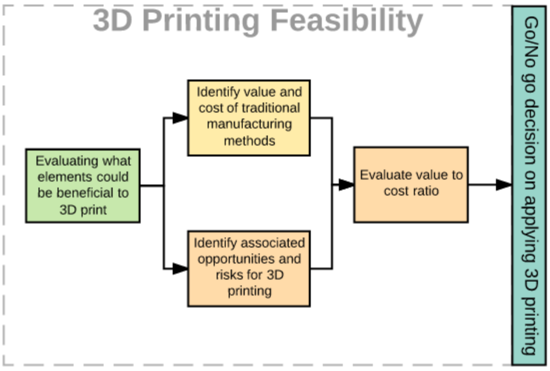


FIGURE 57 ACTIVITIES FEASIBILITY PHASE

Activities/Roles	ARCH	SE	3DPC	PM
Evaluating what elements could be beneficial to 3D print	R	S		
Identify associated opportunities and risks			R	
Identify value to cost ratio of traditional manufacturing methods		R		
Evaluate value to cost ratio	C	C	R	
Make a go/no go decision on applying 3D printing	C	C	C	R

TABLE 16 RASCI MATRIX FEASIBILITY PHASE

Product Definition & Partner Selection
The goal of this phase is to specify the 3D printed component in more detail and form a collaborative agreement between service provider and project manager. Deliverables are an initial product specification and a collaborative contract between the service provider and project manager. Activities are presented in figure 58, the corresponding RASCI matrix is presented in table 17.

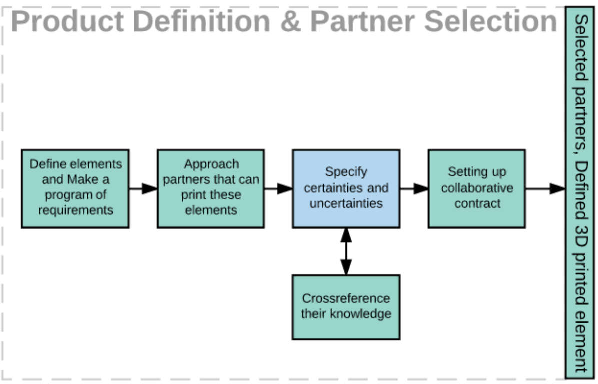


FIGURE 58 ACTIVITIES PRODUCT DEFINITION & PARTNER SELECTION

Activities/Roles	ARCH	SP	PM	LC (o)	PS
Define elements to be printed	R	S	A		C
Determine which elements are to be printed	R	S	S		
Make a program of requirements (output specification) for these elements	R	S	S		
Select partners that can print these elements	S	I	R		
Specify supplier's certainties and uncertainties	I	R	A		
Cross reference their knowledge	I	S	R		
Setting up (collaborative) contracts	I		R	C	

TABLE 17 RASCI MATRIX PRODUCT DEFINITION & PARTNER SELECTION

1. Define elements to be printed
    a. Determine which elements are to be printed
    b. Make a program of requirements (output specification) for these elements

This product definition is done jointly between service provider, project manager and project architect and is more detailed than in the feasibility phase.

2. Select partners that can print these elements
    a. Ask potential partners to specify their certainties and uncertainties
    b. Cross reference their knowledge

At the current development stage, the best service provider to select is one where the visionary organization investing in its technology development has ambitions aligned with the objectives of the project. This reduces the chances of later conflict and allows for distribution of risk and reward required for the innovation.

During partner selection, cross referencing the stated knowledge and experience of the service provider increases the reliability of their stated their certainties and uncertainties, therefor reducing risk.

3. Setting up collaborative contracts

A contract should be set up in a way that allows the service provider and client to collaborate rather than having a hierarchical relationship. Agile contracts or other alternative contracting methods can be used (see Vergaderfabriek case).

Technology Development

Technology development projects can occur in a wide variety of forms and will likely have to be done in multiple stages in the project. The activities described in figure 59 are the minimal requirements that have to be met before applying 3D printing. Ideally these activities have already been done by the service provider prior to project start, though some can also be done in parallel to the design for the 3D printed component.

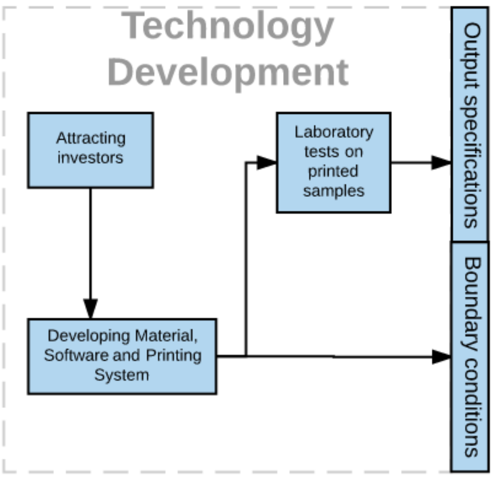


FIGURE 59 ACTIVITIES TECHNOLOGY DEVELOPMENT

Activities/Roles	SP	SM	SD	MS	MT	MC (o)	PS
Attracting investors	A						I
Developing material, software and printing system	A	S	S	S	S	C	I
Supply of printing system		R					
Supply of material				R			
Supply of software packages and related expertise			R				
Obtaining Output specifications	A			S	R	C	I
Obtaining Boundary conditions for the technology	A			S		C	I

TABLE 18 RASCI MATRIX TECHNOLOGY DEVELOPMENT

The goal of this phase is to obtain concrete information on the output specifications and boundary conditions of the manufacturing technology. Deliverables might include certification documents and material performance data. These serve as input for the engineer to make design calculations and dimensioning of the 3D printed object. Activities are presented in figure 59. Responsibilities for the individual activities is presented in the RASCI matrix in table 18.

Important to know here is that every time a manufacturing parameter is changed, the tests will have to be redone to certify the "new" manufacturing process. This is the main reason why multiple of these projects might have to be done during the product design phase.

Though represented as a sequential process, The activities in figure 59 have a strong interaction. There will be a high amount of iterations between them. The governance approach innovation should therefore be maintained for it.

1. Attracting investors

Finances are required to develop the technology. Visionary organizations must be sought who aim to transform their industry by developing a new type of product or service. Visionaries can be recognized from all players in the industry, who aim to develop different types of business cases. These organizations can have a steering function in the project for which the technology will be used. Important to consider therefore is the underlying incentive of your investor and aligning future projects with it.

2. Developing material, software and printing system

Developing 3D printing technology requires active interaction between software (to steer the robots or printer), hardware (the printers) and the materials. Optimizations of manufacturing parameters can be reached through rapid experimentation (for example increasing speed and testing whether strength is reduced).

3. Obtaining Output specifications

Assuming a direct printing (rather than mold printing) approach, laboratory tests should be conducted on printed samples so that output specifications can be communicated to the engineers who design the product. Parameters obtained can vary from mechanical (strength, stiffness) to functional (thermal, acoustic).

4. Obtaining Boundary conditions for your technology

Making shapes in any material, size and shape is a compelling future to strive for, but not yet possible. The limits of the manufacturing technology (inclination angle, size, material) should be clear so that designers can take these limitations into account during the design process.

Printing Strategy

The goal of the printing strategy phase is to make high level design decisions that provide general frames and boundaries to the design space, and determine a workflow for the 3D printed component. It is key to involve all relevant disciplines at this stage, which should minimally consist of the manufacturer, structural engineer (+ permit provider), contractor, and the project manager. Activities are presented in figure 60, the corresponding RASCI matrix is presented in table 19.

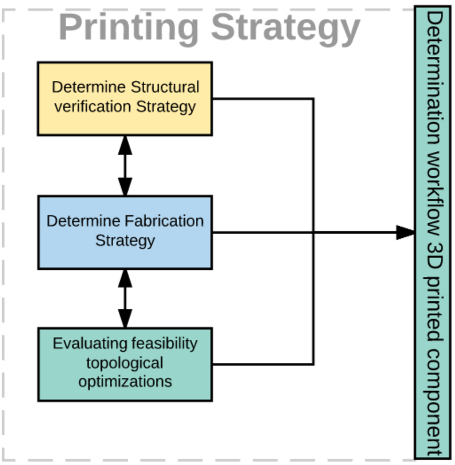


FIGURE 60 ACTIVITIES PRINTING STRATEGY

Activities/Roles	SP	ARCH	SE	CONT	PM	PP
Decide on a structural verification strategy	S	I	R	I	I	C
Fabrication strategy	R	S	S	S	C	
Evaluating feasibility topological optimizations	S	C	S		R	
Decide on a workflow for delivering the required expertise to the component	S	C	C	C	R	

TABLE 19 RASCI MATRIX PRINTING STRATEGY

1. Determine a structural verification strategy

A joint strategy should be formulated to structurally verify the component. This is a key project risk that is best addressed in the early design stage. Potential activities are formulated in paragraph 8.2. structural verification. The best fit will depend on the project goals, the available resources and the team's willingness to bear risk.

2. Fabrication strategy

The fabrication strategy consists of a number of decisions that provide general frames and boundaries to the design space, and determine a workflow for the 3D printed component. A decision should be made for a geographical location of production and assembly. Limitations of each discipline should be taken into account.

3. Evaluating feasibility topological optimizations

Functional optimizations can result in additional functionality for the component or reduced material cost. However, the time spent on optimization results in additional cost. An assessment therefore has to be made on what type of optimizations will be done for the project and whether the added value outweighs the associated design cost.

Design (functional and for manufacturing)

The goal of this phase is to make a virtual representation (3D Model) of the 3D printed component which is optimized for functionality, manufacturing and assembly. Functionality could be in the form of aesthetics, structural performance, acoustics, thermal conductivity or a combination of the above. Deliverables include the 3D files that can be directly manufactured, and instructions for assembly and installation on site. Activities are presented in figure 61, the corresponding RASCI matrix is presented in table 20.

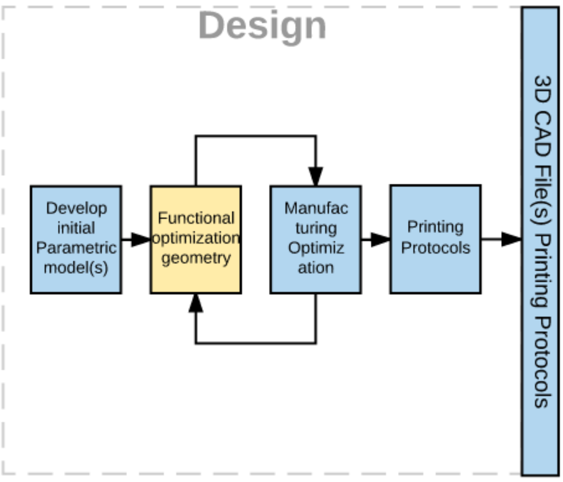


FIGURE 61 ACTIVITIES DESIGN PHASE

Activities/Roles	SP	ARCH	SE	CONT	PM	PP
Develop an initial parametric digital model for the product	R	C			I	
Mathematically define the desired aesthetic shape	R	C				
Incorporate boundary conditions from manufacturer (size, inclination angle)	R					
Integration with overall design	S	A	S		I	
Functionally optimize the geometry	S	I	R			
Define the load case	I		R			
Perform topological (structural) optimization	S		R			
Optimize the geometry for manufacture and assembly	R		S	R		
Preparation construction planning	S			A	I	
Creating printing protocols	R					
Integrating printing protocols with overall construction planning	S			A		

TABLE 20 RASCI MATRIX DESIGN PHASE

Iterations should be purposefully planned between the functional optimization and the manufacturing optimization. It should be noted that due to the fact that there is one (digital) version of the design, this model can be easily shared between designer and manufacturer. Even if the project actors are at different geographical locations, it is still feasible to do multiple iterations so that both type of requirements are optimally balanced for the 3D printed component.

1. Develop an initial parametric digital model for the product

If the printed element consist of one file, this is fairly straight forward. For larger elements that are assembled from smaller 3D printed objects, a PLM approach should be used, similarly to BIM. This results in one central 3D model in which the overall design information is stored. Project stakeholders can then check out individual files, modify and reinsert them. As the size of the component increases, so does the complexity in its management and communication protocols.

   a. Mathematically define the desired aesthetic shape

This can be done by looking for mathematical equations that describe the geometry that is desired. Later changes can then be quickly incorporated.

b. Incorporate boundary conditions from manufacturer (size, inclination angle)

These are the same boundary conditions that result from the technology development phase described earlier. These boundary conditions provide limitations to the design space for the components and should therefore be scripted in the overall model.

2. Functionally optimization geometry

Functional optimizations of the component which are decided upon during the printing strategy phase are now executed. Design software can contribute to the execution of topological optimizations to reduce material use or increase the functionality. The suggested sub activities are an example of optimizing a component for structural performance, though other optimizations are also possible.

a. Define the load case
b. Perform topological (structural) optimization

3. Optimize the geometry for manufacturing and assembly

The functionally optimized shape is then optimized for manufacturing and assembly. If the service provider does not have the expertise for assembly in-house the project contractor should be consulted.

4. Preparation construction planning

The assembly and installation of the 3D printed component on site requires integration with the overall planning, which should be communicated to individuals responsible for (or influenced by) the activities.

a. Creating printing protocols
b. Integrating printing protocols with overall construction planning

Manufacture
The goal of this phase is to translate the virtual 3D printed model into a physical object which can be delivered to the contractor of the overall project. Activities are presented in figure 62, the corresponding RASCI matrix is presented in table 21.

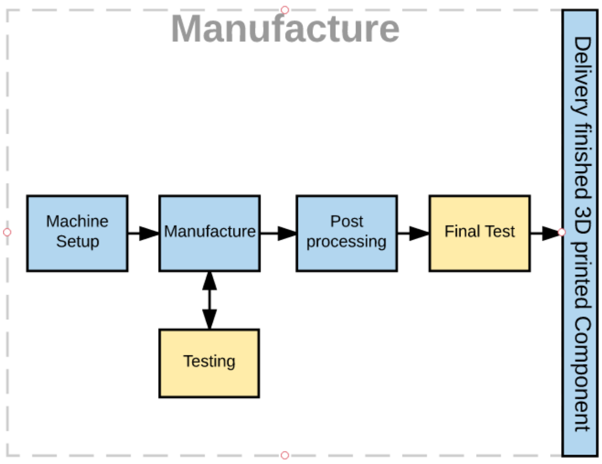


FIGURE 62 ACTIVITIES MANUFACTURE

Activities/Roles	SP	CON	SE	MS
Machine Setup	R			
Ensuring printing conditions	R			
Mobilize printing system	R			
Calibrate printing system	R			
Manufacture	R			S
Manufacturing of object(s)	R			
Tests during manufacturing process	S		R	
Post processing (Cleaning and finishing)	R			
Assembly, Transport and Installation	R	A		
Transport	R			
Assembly	R	S		
Installation	S	R		
Structural verification test (proof loading)	S	S	R	

TABLE 21 RASCI MATRIX MANUFACTURE

1. Machine Setup

    a. Ensuring right conditions
    b. Mobilize printing system
    c. Calibrate printing system

If an offsite production location is chosen, the machine setup requires little effort. If the elements are printed on site however, a calibration of the system in this new environment required. Printing requires certain conditions like a constant temperature (influencing the material properties), and shelter from weather conditions.

2. Manufacture
    a. Manufacturing of object(s)

At the push of a button, the printer starts manufacturing the object. Depending on the fabrication strategy, the element can be produced offsite, directly on its desired position on site or on a different place on the construction site (mini factory).

    b. Tests during manufacturing process

Tests should be conducted in parallel to the manufacturing process to reduce the risk that the product does not meet the requirements during the final test.

3. Post processing
    a. Cleaning
    b. Finishing

Post processing is required to reach the desired level of surface quality of the 3D printed component. At the moment this is often done manually.

4. Structural verification test

The extent to which tests on the final product are required will depend on the requirements of the permit provider. If multiple similar type of elements are printed, the testing might only have to be done on one element.

5. Assembly, Transport and Installation
    a. Transport
    b. Assembly
    c. Installation

Detailed responsibilities related to transport, assembly and installation on site depend on the geographical location in which they occur. If the activity is performed in the service provider's factory, it should be allocated to the service provider. If the activity is performed on the construction site, it should be allocated to the contractor. In practice, the two would ideally collaborate as their expertise can both be utilized.

8.4.4 Interfaces

The milestones of the separate project layers are not independent of each other, they have interfaces. This sub paragraph identifies the interfaces between the project and 3D printed component and the interfaces between the technology development and component layer, and suggests how to manage them.

In literature two types of interfaces can be found (Archibald, 1976):

- Product interfaces (performance of subsystems into overall systems, and physical integration of subsystem into the overall system)
- Process interfaces (changes in responsibility, management, and information handovers)

Interfaces between project and 3D printed component
Product interfaces are the responsibility of the design manager, which is assumed to be the architect in the designed governance structure. In practice this means that the architect should communicate with the engineer working on the component on whether the 3D printed component physically and functionally fits in the overall project.

Several process interfaces should be carefully managed. An important handover in responsibility to manage is the transition from finished 3D printed component to installation on the construction site. Responsibility here shifts from the manufacturer (responsible for manufacturing) to the contractor (responsible for delivery overall project). Elements that should be discussed between these two parties are the transportation, delivery date, assembly (in case of large scale components), and installation into the overall project. The contractor should be accountable for this interface, since he is the one responsible for delivery of the overall project.

A management interface for which the project manager is responsible is the integration of the planning for the component in the overall project planning. The planning resulting from the ambition should be within the resources and time available for the overall project. The project manager has two key milestones in the component process which he can use to gain insight in whether this is the case: the specification of certainties and uncertainties and the determination of the workflow of the component. He should be engaged in the formal closure of both deliverables and potentially change either the planning for the overall project or the ambitions for the 3D printed component.

An information interface is the iteration(s) between the functional design and the design for manufacturing. In practice this means a communication system should be set up to facilitate the exchange of information. For a component which consists of one file this is relatively simple and can be done by the project engineer. If the component consist of many files however, the complexity increases radically. In that case it should be managed by the project manager.

Interfaces between 3D printed component and the 3D printing technology development
An information interface to manage closely is the resulting boundary conditions and output specifications of the manufacturing technology between service provider and engineer. The activities to acquire this knowledge are presented in the phase "technology development" described in this chapter.

Starting such a technology development project should be signed off by the project manager, who ensures that it fits within the planning of the overall project. The (information) deliverables of these projects should be communicated to the engineer designing the 3D printed component, who can use it as input for the functional design of the component. Because the results of a technology development project have to be used in the design phase, it is not useful anymore to start new projects during or shortly prior to the start of construction. This is why in paragraph 8.2 the technology development layer stops during the construction phases.

9 Future development 3D Printing

This chapter presents conclusions related to the future development of 3D printing. It is a synthesis of the current developments, case study interviews, the insights from the 3D printing conference in Amsterdam (see appendix B), and an expert panel workshop within Arup.

The items discussed will be as follows. An overall qualitative description is first given on the expected future role 3D printing will have in the construction industry in paragraph 9.1. Conditions and accelerating drivers for its adoption are then presented in paragraph 9.2. An explorative qualitative description of a governance structure for a future scenario in which the majority of a building is 3D printed is then presented in paragraph 9.3. Expected changes in the role of project manager as a consequence of applying 3D printing are presented in 9.4. The role of Arup in the innovation process and projects in which 3D printing is applied is discussed in paragraph 9.5. An overall conclusion is finally provided in paragraph 9.6.

9.1 Short and medium term development of 3D printing in the construction industry

This paragraph presents conclusions on what the short term (0-2 years) and medium term (2-5 years) development for 3D printing in the construction industry is expected to look like. It should be noted that the future development for 3D printing is highly uncertain, both in general as for the construction industry. Frank Piller, professor and author of a paper on a Delphi study on the future of 3D printing (Jiang, Kleer, & Piller, 2017), stated in a conversation at the 3D printing conference that where normally a Delphi study leads to a consensus on experts, his study did not. The perspective outlined here is based on analysis of the maturities that were measured during the case studies, the identified challenges, and the current developments and trends identified in literature (4.6.4).

Short term development (0-2 years)
3D printing will not play a significant role in the near future (0-2 years). At the moment, the construction industry is too fragmented and risk averse, the amount of challenges are still high, and the maturity of the processes is low. For the manufacturing industry however, 3D printing will play a significant role. Their leading role in developing the technology and introducing competitive applications in the market will drive developments in the construction industry.

Medium term development (2-5 years)
In the medium term (2-5 years), introduction of both development scenario's as described in paragraph 4.6.5 is expected. These are applying a number of 3D printed components in a construction project and 3D printing the majority of a building. The reason these will see an introduction is due to enabling digital technologies and trends that are developing independently of 3D printing, of which the most significant are BIM, the integration of the project value chain and the R&D from the automotive and aerospace industry.

Though which niche market will 3D printing be adopted?
During the expert panel meeting, Kluwer (Senior Project Manager Arup) stated that in finding the next component to be 3D printed, it is important to look where money is spent in the current production process, and how 3D printing could reduce it. The opportunity for product integration is highest for components with a high degree of complexity. A second consideration is the risk adversity, meaning mature technologies (small scale, plastics) are likely to be introduced sooner than large scale components. Keeping these considerations in mind, two niche markets through which the technology is expected to be adopted in the construction industry are small scale steel joints for facades and structures and polymer ornaments. During the expert panel meeting and XtreeE workshop, walls with integrated functionality were also mentioned. This could reduce the number of components and thickness of the overall wall, resulting in more square meters of living space and therefore more revenue.

For these niche markets, holistic services can be developed. Once these are mature, it reduces the threshold for other applications. Since there are many different types of construction projects and each project consist of many different components, introduction of 3D printing is unlikely to replace traditional manufacturing methods. Rather, it will complement existing (digital) manufacturing technologies and be competitive for specific components and projects.

Parallel developments introduce an additional niche market that is valid for the second future development scenario: affordable housing. A governance structure for such a project is presented in paragraph 9.3. First though, the conditions that should be met for adoption in the construction industry are discussed.

9.2 Conditions and accelerating drivers of 3D printing adoption

If the conditions in this paragraph are met, 3D printing will be adopted in the construction industry. All are either increasing the value of applying 3D printing, or reduce the associated costs and risk. These conditions are based on analysis of the challenges identified in literature and case studies. In addition to the conditions, several accelerating drivers are mentioned which could speed up its adoption.

A certified manufacturing process
The most important condition for adoption of 3D printing in the construction industry is a certified manufacturing process that consistently produces objects with known material properties. This would largely resolve the innovation to be done during the project, and therefor reduces the risk of applying 3D printing in a project. In the aviation industry, a certified process for structural 3D printed titanium components is expected to be achieved at the end of this year. (Vincent, 2017)

Responsibility for certifying the manufacturing process lies with 3D printing service providers. The process could be accelerated when authorities express a vision to do so, as is being done by the Lloyd's Register Foundation. (Lloyd's Register Foundation, 2016)

Standards and codes for applying 3D printing in construction projects
Currently there are no standards for applying freeform 3D printed components in construction projects, which means that stakeholders wanting to do so have to create their own strategy. This creates a lot of uncertainty and risk. This research contributes to reducing this uncertainty, by delivering an initial framework in the form of a generic governance structure (chapter 8).

An integrated approach towards project delivery
If 3D printing is applied, an integrated approach to the design and manufacturing is an important condition. An integrated approach (like a D&B contract) for the overall project makes it easier to facilitate this. The opposite is also true. If the integrated approach to project delivery is already present (in the form of BIM or integrated contracts), it becomes easier to apply 3D printing. The current trend towards a more integrated project value chain means that the threshold for applying 3D printing will reduce over time.

New skills for project stakeholders
New skills are required for designers to design and engineer for 3D printing in projects, and utilize the freeform possibilities. Educational programs are already being launched for this purpose, like the MSc program Design for Manufacture, launched this year by the Bartlett school of Architecture. (Menges et al., 2017)

Project and design managers should learn how to manage this digitalized design process. Knowledge should be obtained on managing product design processes, with aspects like concurrent engineering and managing iterations. (Cantamessa & Francesca, 2016) Existing BIM managers could also be consulted, who have experience in managing a digital design process within construction projects.

Finally, construction workers must be educated on how to operate and integrate the digital manufacturing systems or components on site. Contractors involved with 3D printing should develop training programs to educate their workers for this purpose.

Examples of competitive applications
The construction industry is very cost sensitive, a condition for its adoption is therefore that the benefits outweigh the associated risk. This is confirmed by Galjaard (digital fabrication expert Arup) and Jonker (tender manager BAM), who state that for 3D printing to be adopted it should be a means to realize more value in a project, rather than a goal in itself.

The additional value that 3D printing has is still difficult to quantify. Complex freeform shapes can be made cheaper with 3D printing than with traditional manufacturing methods, though a rectilinear structure with similar functionality can be manufactured at a much lower cost. Geurtjens, CTO at MX3D states that additive manufacturing (in steel) is unlikely to become more cheap than traditional manufacturing methods, though it can provide additional value in the freeform shapes it can create. At the moment however, a clear demand from the market for freeform objects does not seem be present. Proof of competitive applications or inspiring examples could be an accelerating driver to create this demand with clients, who in turn will be willing to pay an additional price for it.

Creating this demand is an initial role for researchers, who should continue to create artefacts to provide insight in the possibilities of the technology. Visionary organizations should then take responsibility for finding the right application area's in projects for which the technology is competitive to traditional manufacturing methods.

Technological improvements for 3D printing steel and concrete
Technological improvements for 3D printing with construction materials to increase speed and quality and reduce cost are an accelerating driver that will make the manufacturing technology more competitive with traditional manufacturing methods.

The required R&D for these technological improvements will be driven by the aviation, automotive the manufacturing industry. Technological improvements for large scale components in construction materials however should be developed by researchers. The role of organizations within the construction industry is likely to be small, due to the low margins and R&D spending.

Design of new 3D printing construction materials
The design of new 3D printing materials would be an accelerating driver in the adoption of 3D printing in the construction industry. These materials could either fulfill multiple functional requirements (like Geocement (Apis Cor, 2017) or can be printed, shredded and re-used. The development of such materials would be a game changer in terms of sustainability. A role lies here for researchers and material scientists.

A visionary organization willing to invest
Another accelerating driver is the presence of visionary organizations investing in the technology. Developing 3D printing technology, its related processes, design skills requires a substantial investment, which is not competitive for the first project in which it is applied. A large portion of the activities which increase cost when compared to traditional manufacturing technologies only have to be done once. A visionary organization willing to finance the initial project could speed up 3D printing adoption.

Supporting government
A supporting government can be an accelerating driver in the adoption of 3D printing. The vision expressed in Dubai for example of 3D printing 25% of all buildings in 2030 is an example of this. By acting as a client and putting 3D printing as a design requirement (as was done by the R&Drone laboratory) they force the construction industry to innovate. In the short term this might be more costly, in the long term though benefits can be expected from it. An analogy can be observed with the adoption of BIM in the UK. The government drove its adoption with legislation, with the result that a basic level of maturity is now common practice.

Open innovation models
The wide variety of conditions and drivers point to the fact that open innovation models should be incorporated to accelerate 3D printing adoption. It requires interdisciplinary collaboration between many

different organizations and even industries, which cannot be accomplished by adopting structured innovation programs within an organization's individual boundaries. A strategy that visionary organizations should take is to form knowledge networks with partners in the industry, to facilitate the cross disciplinary research and collaboration that is required to apply 3D printing.

9.3 Explorative future governance structure for buildings in which the majority is 3D printed

This paragraph presents an explorative future governance structure for the second development scenario (as specified in 4.6.5), in which the majority of the building is 3D printed. A qualitative description of what such a project will look like and what governance approach is suitable for it is first discussed. (9.3.1) It is then discussed which organization could be responsible for this process. (9.3.2) Finally, it is explained why low-cost housing is a suitable market for it. (9.3.3).

This governance structure was created by means of synthesis of the future opportunities mentioned by interviewees and stated in literature, extrapolation of the trends specified in literature (4.6.4), and the reactions from an expert panel meeting.

9.3.1 Description

A building is constructed utilizing an industrial approach with 3D printing as the main manufacturing technology. This main manufacturing technology is complemented by traditional and other digital fabrication technologies, which together form the overall structure.

The process starts with a manufacturer developing a flexible manufacturing process, which will require a substantial R&D investment. In collaboration with suppliers who produce the components that are not suitable to be 3D printed[10] and the structural engineer which can provide input on the structural validation of the building, a system that can consistently produce a variety of houses with the same manufacturing processes is developed. The developed system results in a design tool with incorporated boundary conditions for the production technology, which limit the total design space.

With this design tool, the client designs his own house, empowered by advanced software tools. With the tool he can easily customize the house according to his unique requirements (like floor area, wall thickness, orientation, sustainability). The client is responsible for obtaining the land, though he can request expertise from the manufacturer. His design results in a digital file that is sent to the engineer within the manufacturers organization.

The engineer validates whether the building is safe for the unique location. Small adjustments might be required in collaboration with the client. After validating this design, the digital 3D model is ready for construction.

The manufacturer constructs the building as designed by the client. Partnering suppliers are engaged to deliver specific aspects, though the majority can be done with the manufacturer's 3D printing technology.

This process is characterized by:

- An integrated delivery, the client deals with one organization.
- Fast lead time, design work is very limited, the amount of steps between the design and manufacture is very small
- Low cost. Because the manufacturing process is optimized for the designs that can be made by the tool, and design and engineering activities are very limited and mostly automated, the building can be made at a low cost. Similarly to the automotive industry, the whole process (in terms of

[10] Jonker (BAM tender manager) noted that there will always be a need for supplier of individual components. A building consist of a large amount of different (increasingly smart) components, which are simply inefficient to be manufactured by one organization.

organization, design, interface management) is thought out beforehand, meaning its resulting buildings can be made cheaply.

Though in theory such a process would be possible with other manufacturing technologies, 3D printing offers several unique features that make it more feasible.

- Integrated components reduce the number of components, therefor reducing the amount of (assembly) activities on site
- 3D printing can make unique products with the same production process. This means that the customization demand of housing can be fulfilled while staying in the same production process (which can be optimized and innovated).
- Integrated components reduce the number of components, which means that less different suppliers are needed. This simplifies the project supply chain, making it easier for one organization to take responsibility for the overall process.

The governance structure for developing such a manufacturing process will require substantial innovation to be done. Governance domains that are expected to be utilized during this development time are that of product design and primarily innovation.

9.3.2 Who will be "the manufacturer"?

In the scenario outlined in the previous paragraph the traditional roles of architect, engineer contractor and manufacturer still exist in the process, the key difference from traditional practice though is that they are now taken on by one dominant organization: the manufacturer. Interestingly, any of the existing organizations can become this manufacturer, even organizations external to the construction industry. The expert panel did not reach consensus on which organization will lead the process towards such a scenario.

Because a product development process requires large capital investments, architects and engineers are unlikely to take a leading role in developing it (unless they find an external financier). A large contractor, manufacturer (from 3D printing industry), or real estate developer is a more likely candidate in this sense, because these players have more financial capital available. Another element to consider is the existing expertise required to make it happen. A holistic service from A-Z for the client should be developed, while organizations traditionally only focus on one small part of this service due to the fragmented nature of the design process. Firms with an holistic approach towards design and manufacture possess a lot of the expertise already, meaning little external expertise has to be bought. Examples of such firms are Arup or large contractors.

The expert panel disagreed with the statement that the organization taking responsibility for this integrated service would be an IT firm. According to Ren (Senior designer and digital fabrication expert Arup), an IT firm provides a workflow for a product or service, but not the product itself. The product is what architects, engineers and contractors can provide. He expects IT knowledge requirements for engineers to increase radically though, so that there can be an integration between IT and engineering and design. Jonker thought this would be possible, since it is not about the product, but the need that it fulfills. As soon as an IT firm is better able to fulfill this need, the organization could be an IT firm.

9.3.3 Suitable Market

The governance structure will co-exist with traditional approaches to construction, as these will remain more suitable for large projects characterized by a high degree of uniqueness and scale. The niche market through which the governance structure is expected to emerge is the residential housing market in low income areas. There are four reasons for this:

- The size of dwellings is limited and comparable. Within this outer size there are large customization demands.
- Developments can already be observed in which customers can digitally design their own houses (BPD, 2017)

- There is a huge need for affordable housing, particularly in lower income areas (outside the western world) where people forego other essential needs in order to afford a roof over their head. Mckinsey expects the number of households in this position to grow to 440 million in 2025. (Woetzel, Ram, Mischke, Garemo, & Sankhe, 2014) When assuming construction cost of 30.000 $ per house, this constitutes a potential market of 13,2 trillion dollars. This large market could justify the large capital investment required for it.
- Requirements for low income area's in developing economies are lower

9.4 Changes in the project manager role

In the governance structure for applying the 3D printed components, additional skills are required for the project manager. First, he has to use a fit for purpose approach for managing the overall project, its 3D printed component and the technology development projects. This requires additional training in product development processes and agile approaches. This will allow him to plan for the opportunities and mitigate the additional risk that 3D printing brings to the project. Examples of elements of the product design process that the project manager should become trained in are the management of iterations, concurrent engineering, and product lifecycle management systems.

In the second governance described in the previous paragraph, a project manager is in principle no longer required, because the procedures are standardized. This does not mean that project managers in general are no longer required, for other types of projects it will remain an important role.

9.5 What does this mean for Arup?

This paragraph elaborates what 3D printing could mean for Arup in the coming 5 years, by presenting four potential future business models.

The 3D printing market is growing, and is expected to be applied on an increasing scale in the construction industry. EY surveyed 900 companies on several aspects related to 3D printing. (EY, 2016) 24% of these see 3D printing as a strategically important topic, while 36% has considered adopting 3D printing or already have experience with it. The two main barriers for adopting 3D printing were the large investments and high prices (40%), and the lack of qualified expertise (28%). The latter is where Arup could provide value to future clients.

Arup is a knowledge intensive engineering firm, with a lot of in-house expertise, affinity to innovation and digitalization. Furthermore, it is independent. These characteristics combined with the demand from the market result in the following potential business models:

- Co-developing a 3D printed service or product
- Consultancy services on 3D printing feasibility
- Design and engineering services for large-scale 3D printed components
- Design and engineering of 3D printing production plants

Co-developing a 3D printed service or product
Co-developing a 3D printed service or product can be done in partnerships with existing 3D printing service providers. Arup's affinity with design, engineering and IT could be helpful in creating programs in which clients can design their own products (or houses). A potential high reward product development process is that of the governance structure described in this chapter, which could be co-developed between Arup and a large manufacturer or contractor. If Arup could find an external investor, it could also be leading this process.

Consultancy services on 3D printing feasibility
Consultancy services on 3D printing feasibility are expected to be increasingly requested by clients who want to apply 3D printing in their construction projects. For now the value to cost ratio of applying 3D printing is very often lower than for traditional manufacturing methods. As the technology matures

however, these ratio's will come closer together. Arup could provide value here by consulting clients on potential application area's in their project, including associated risks and opportunities. Their differentiating nature is the fact that they are independent (unlike service providers) and have affinity with both 3D printing and the construction industry.

Design and engineering services for 3D printed components
Design and engineering of 3D printed components becomes interesting particularly when large scale 3D printed components are applied. In principle, service providers do not have structural engineering expertise in-house, meaning they are likely to look for partners that have affinity with 3D printing and structural engineering.

Design and engineering of 3D printing production plants
Design and engineering of 3D printing production plants is a role that is required if 3D printing becomes mainstream in the production sector. Because it is possible to make customized products with few steps integrate products, it is seen by some as an opportunity to bring back production to Western Europe. (EY, 2016) The design and engineering of these plants would be an innovative venture for which Arup could be a valuable partner.

9.6 Conclusion

Both scenario's for projects in which 3D printing is applied are expected to be adopted in the construction industry in the medium term (2-5 years). The reason why adoption is not expected in the short term is because of the conservative nature of the construction industry and the significant amount of existing challenges for large scale 3D printing. In the medium term however, independently developing trends will drive adoption in the market. These trends are related to digital technologies, trends in the construction industry, and the R&D done in the aerospace, automotive and manufacturing industry.

When assessing the conditions and accelerating drivers for adoption of 3D printing, developments on the individual elements can already be observed. Bringing these together will require an open innovation approach in which different organizations and disciplines jointly drive its adoption. Jager, an innovation consultant and project coordinator of the Vergaderfabriek stated that *"The organization that is first to organize all different disciplines in a project, is the one who will win the competition"*. An important role in the process of adopting 3D printing in the construction industry is that of a new type of project manager.

Arup can play a role in the adoption process through co-development of the scenario in which the majority of the building is 3D printed. In the short term it is not recommended to do so, given the large amount of limitations. Rather, Arup is recommend to participate in innovation networks to acquire the associated skills and expertise. In future projects in which 3D printing is applied, Arup can have several roles. It can provide Consultancy services on 3D printing feasibility, Design and engineering services for 3D printed components. Finally, it can play an important role in the design of 3D printing production plants, which are expected to be in demand when the transition toward end-product manufacturing is made.

10 Conclusions and recommendations

The purpose of this research was to answer the following main research question and its sub questions:

"What is the impact of large scale freeform 3D printing on the governance of functional construction projects?"

1. What does the governance of a project in which 3D printing is applied currently look like?
2. What are the current differences between the governance of a project in which 3D printing is applied and a traditional construction project?
3. What is a potential governance for a project in which 3D printing is applied?
    a. What is currently a potential governance structure for a project in which a number of 3D printed components is applied ?
    b. What is a future potential governance structure for a building in which the majority of its components is 3D printed?

Detailed answers to these research question can be found in the chapter 6 (RQ1), chapter 7 (RQ2), chapter 8 (RQ3a), and paragraph 9.3 (RQ3b). This chapter discusses the main conclusions to all research questions and a perspective on how 3D printing will develop in the future.

What does the governance of a project in which 3D printing is applied currently look like?
Three different governance domains can be recognized when applying 3D printing in a construction project: traditional construction project, product design, and innovation. These domains all have different characteristics, as described in figure 63.

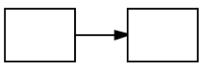
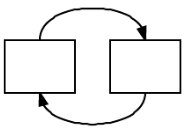
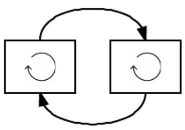
Governance Domains	Phases & Activities	Roles and Responsibilities	Organizations	Characteristics
Construction Project		Defined and rigid	Multiple Organizations Fragmentation	Structured Hierarchy
Product Design		Defined and flexible	In-House Collaboration	Structured Network
Innovation		Defined ad-hoc	In-House Integration	Flexible Network

FIGURE 63 GOVERNANCE DOMAINS FOUND IN CASE STUDIES

The governance domain construction project is characterized by a rigid fragmented stage-gate process, with hierarchical relationships among project actors. The governance domain product design is characterized by a flexible stage-gate process which allows for iterations between the phases. All relevant disciplines are involved early and work collaboratively towards the final product. The governance domain innovation is characterized by an agile approach, with iterations not only between phases, but also activities. The whole process is even more flexible, detailed activities are defined ad-hoc. Small multidisciplinary teams closely collaborate in the innovation process.

Based on analysis of the phases, activities, roles and responsibilities governance domains were identified for 7 case studies, which are presented in figure 64.

Case Study	Governance construction project	Governance product design	Governance innovation
3D-Printing in the Circular City		X	X
De Vergaderfabriek		X	X
R&Drone Laboratory	X	X	X
MX3D Bridge		X	X
The Great Pagoda	X	X	
Post Aix-en-Provence School	X	X	X
Landscape House	X	X	X

FIGURE 64 GOVERNANCE DOMAINS OBSERVED IN ALL CASE STUDIES

4 case studies suited the first scenario in which 3D printing was used for components in a construction project. Its governance approach was a combination of elements from traditional construction projects, product design and innovation. The similarities to product design include an early involvement of the manufacturer, iterations between the design phases, and network relationships between project stakeholders. The different disciplines collaborated closely towards realization of the 3D printed component. Similarities to innovation were the dynamic unstructured process, iterative experimentation with the technology, an ad-hoc style of management, and changing composition of project teams.

2 case studies suited the second scenario in which 3D printing was used to manufacture the majority of the building. Its governance approach was a combination of product design and innovation. From this it can be concluded that traditional governance of construction projects is not valid for design, engineering and manufacturing of a 3D printed object, regardless of whether it is a small component or a building. Once 3D printing technology is mature in the future, the governance domain innovation will drastically reduce, meaning the governance approach for this scenario will converge to that of product design.

After coupling the scenario's to the observed governance types, the governance for projects in which 3D printing is applied looks as described in figure 65.

Project type	Governance construction project	Governance product design	Governance innovation
Traditional construction project	X	(X)	
3D Printed Component		X	X
Construction project with 3D printed component	X	X	X
Construction project where majority of components is 3D printed		X	X

FIGURE 65 CURRENT IMPACT OF 3D PRINTING ON PROJECT GOVERNANCE

Project type	Governance construction project	Governance product design	Governance innovation
Traditional construction project	X	X	
3D Printed Component		X	
Construction project with 3D printed component	X	X	
Construction project where majority of components is 3D printed		X	

FUTURE IMPACT OF 3D PRINTING ON PROJECT GOVERNANCE

Governance structures were designed for the scenario's highlighted yellow in figure 65. A governance structure for a current project in which a number of 3D printed components are applied, and a governance structure for a future project in which the majority is 3D printed. The first governance structure is fully operationalized in its phases, activities, roles, responsibilities and interfaces. The second governance structure is explorative and described on a high level.

What are the current differences between the governance of a project in which 3D printing is applied and a traditional construction project?

Applying 3D printing in a current project results in several concrete differences in its overall governance. These can partly be explained by the additional governance elements of product design and innovation. Concrete implications of applying 3D printing in a current project are a central role for the manufacturer, standard contracts and design phases are not applicable, increased uncertainty and risk, an alternative building permit acquisition procedure, new required skills for project stakeholders, and an additional information system. In this paragraph, the implications of these differences on project governance are described.

- Central role of the manufacturer

The manufacturer that is normally at the far bottom of the hierarchy now becomes a central part of the design process for the 3D printed object. The manufacturer should be involved at an early stage and the project team should actively collaborate with him. By collaborating, the associated risks and interfaces of the component to the overall project can be better defined, managed and utilized.

- Standard contracts are not applicable

Application of 3D printing requires close collaboration not only with the manufacturer, but also between with all other disciplines that provide input to the 3D printed component. A new type of contract between manufacturer and project team is therefore required, which is more collaborative and reflects the increased responsibilities of the manufacturer. Furthermore, agreements on the rights related to confidentiality of information and intellectual property should be made between all organizations participating in the design and manufacture of the 3D printed component. If 3D printing is applied for a component in the project, an integrated contract for the overall project is most suitable to facilitate the required close collaboration between disciplines.

- Traditional design phases are not applicable

When product design principles are applied to the development of a 3D printed object, progress in terms of deliverables no longer progresses in a linear fashion (increasingly detailed output of drawings). The only tangible deliverable is the finished 3D model and preliminary statuses of the model. This requires a high level of trust from higher management layers and outsiders, who don't obtain intermediary deliverables. An example how this trust can be facilitated is by actively involving them in the development process, so they understand the progress that is being made.

- Increased uncertainty and risk

A development process for a 3D printed object contains a lot of uncertainties and risks, which can either negatively or positively influence project outcomes. Significant risks that negatively influence project outcomes and are normally not present in construction projects are an immature 3D printing technology, alternative building permit acquisition procedures and little experience of project stakeholders. Examples of risks positively influencing project outcomes are reduced lead time of the 3D printed object, increased transparency and mutual understanding between disciplines, and increased flexibility for changes. Utilizing the positive risks and mitigating the negative risks increases the importance of risk management in a project.

- Alternative building permit acquisition procedure

If an uncertified manufacturing technology is used, the material properties are unknown and traditional codes and standards cannot be used. This requires an alternative procedure for obtaining a building permit for the 3D printed object. To increase chances of obtaining the permit, the local municipality should be involved at an early stage to agree on alternative requirements for the grant of the building permit.

Responsibility for obtaining it should be allocated to the lead project engineer or project manager, who should develop a structural verification process in collaboration with the municipality.

- New skills for project stakeholders

If a project team does not have experience with 3D printing, it requires several project stakeholders to develop new skills during the project. During a project kickoff meeting, responsibilities for each of these parties related to the 3D printed component should be communicated, and an inquiry should be made on what knowledge each actor still has to develop. Based on this, time should be reserved for education and development of associated skills.

- Additional Information System

In traditional construction projects the primary method for exchanging information are 2D drawings and documentation. For 3D printing, communication occurs in preliminary 3D models. This requires a different information system, which has to be aligned with the information system of the overall project. Ideally, the overall project would apply BIM and also communicate in 3D models. If this is not the case, responsibility should be allocated to individuals assuring that the 3D models align with the 2D drawings of the overall project.

What is currently a potential governance structure for a project in which a number of 3D printed components is applied?

A project in which 3D printed components are applied should be decoupled in three layers: the overall project, the 3D printed component(s) and the 3D printing technology. A fit for purpose governance approach should be used for each individual layer. The layers and their accompanied governance approach are presented in figure 66.

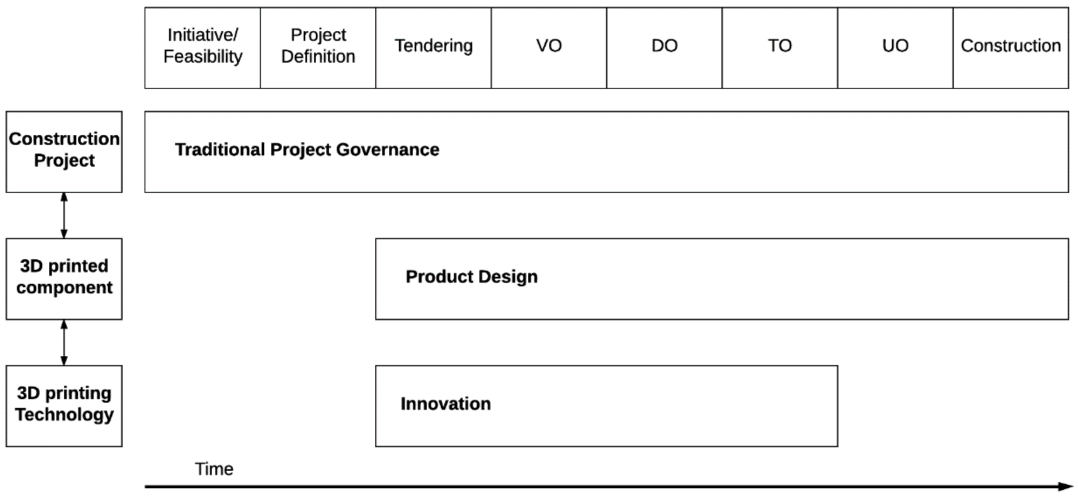


FIGURE 66 GOVERNANCE FOR A PROJECT IN WHICH 3D PRINTED COMPONENTS ARE APPLIED

On the level of the construction project, an integrated contract can best be used. This facilitates the required holistic design process, leaves more room to involve the manufacturer early and actively in the design process, and leaves sufficient time for any potential technology development projects required for the immature printing technology. The decision to apply 3D printing is best done as soon as a general description of the component is made, of which the tendering stage is the earliest possible moment. If more mature processes and technologies are used, it can also be introduced in a later stage in the project.

The 3D printed component has to be designed and manufactured utilizing the governance of product design, to facilitate the close collaboration between disciplines, iterations between design phases and active involvement of the manufacturer.

If the 3D printing technology is not yet mature and requires additional development, the governance domain of innovation should be applied. This allows for more flexibility, room for experimentation and is aligned with the associated uncertainty. As soon as the construction stage is entered, technology developments for the project should no longer be initiated, as there is no more time to incorporate the results in the design.

A full operationalization in which phases, activities, roles, and responsibilities was made, based on analysis of the best practices, challenges and opportunities observed in the case studies. The resulting interfaces of decoupling the project into three layers were identified and responsibility for them was allocated to the existing roles.

What is a future potential governance structure for a building in which the majority of its components are 3D printed?

An explorative governance structure in which the majority of a future building is 3D printed is designed in this research. In such a project, buildings will be constructed by an industrial approach in which 3D printing is the main manufacturing technology. In the manufacturing process, 3D printing is complemented by other (digital) fabrication technologies, which together form the overall structure. Within the boundaries of the manufacturing capabilities, clients will design their own building using digital design tools. An engineer will then validate whether their design is safe for the unique location of the building, after which the manufacturer will manufacture the building. This would drastically reduce cost and lead time of the building, since the same (optimized) process is used for every project. The whole process is led by one organization. This could be any organization, both within and from outside the construction industry.

This scenario would be difficult to realize with traditional manufacturing technologies. A project now consists of many different types of components (and suppliers), and a relatively large amount of steps is required from initial conception towards actual manufacturing. With 3D printing the amount of components (and suppliers) can be reduced, as well as the number of steps from conception to manufacturing. This reduces complexity and makes it easier for one organization to take responsibility for the whole process. Given the flexibility of its manufacturing process, unique client requirements can be met while using the same manufacturing process. A potential market which is suitable for such a process it is the low cost residential housing market. The outer size is limited and comparable, developments can already be observed in which customers digitally design their own houses, and there is a huge market for it which would justify the large initial capital investments.

Future development
3D printing shows strong couplings to other digital technologies and enabling trends in the construction industry, which will develop independently of 3D printing. The most important are BIM, the integration of the project value chain and the R&D done by the aerospace and automotive industry. Due to the conservative nature in the construction industry and the low maturity of the technology, little adoption of 3D printing is expected in the short term (0-2 years). In the medium term (2-5 years) both scenarios are expected to be introduced in the construction industry, starting with the application of 3D printed components.

Recommendations
Clients considering whether 3D printing has value are recommended to read the conclusions of this report and conduct a feasibility study before deciding to apply 3D printing. This provides insight in the risks and opportunities associated with the technology, based on which an informed decision can be made on whether or not to apply 3D printing. This decision will always be project specific. At the moment 3D printing is often not competitive to traditional manufacturing technologies.

Practitioners that chose to apply (or are applying) 3D printed objects are recommended to use a product design approach. If a 3D printed component is applied in an overall construction project they are recommended to apply the operationalized governance structure outlined in this research as a starting point on which detailed allocation of responsibilities can be based.

Visionary organizations aiming to use 3D printing for the majority of a building are recommended to develop larger business cases with their developed technology, of which the second scenario outlined in this research is an example.

To drive the adoption process for 3D printing, open innovation models are recommended to be applied, which facilitate the cross disciplinary required innovation. Innovators should be encouraged to form partnerships with universities and organizations outside the construction industry, to fully exploit the potential of 3D printing.

The collective body of existing research and potential directions for further research is very large. The recommendations for further research originate from the added value of this research:

- Develop the explorative governance structure outlined in this research in more detail, by creating a proof of concept
- Refine the operationalization of the governance structure by validating it against mature case studies

11 Discussion

Implications research

This research showed that generic design and management principles can be identified for the application of 3D printing in construction projects, independent of the application area or 3D printing technology. Projects in which 3D printing is applied have a wide variety of characteristics. Previous research was often primarily oriented towards a specific technology or application area. The governance framework designed in this research is more generic and therefore be used as a starting point for further refined models for specific technologies.

The research presents a hands-on method on how to apply 3D printed components in a construction project. This complements existing theoretical perspectives with a practical one. It was able to do so through a practice oriented research, collecting empirical data from real construction projects in which it was applied. Previous practice oriented research originated largely from research projects. This emphasizes the product, but does not take into account the business context.

This research provides a holistic perspective about what (business) conditions have to be met before 3D printing can be applied in a project. According to Moore, both business and product conditions have to be met before a mainstream customer applies a disruptive innovation. (Moore, 2014) These business conditions were in part present from an industry perspective (IDEA Consult, AIT, VTT, CECIMO, 2016), but available in limited amounts for specific projects. This awareness increases the likelihood that a visionary organization will decide to invest in the technology, which is an important accelerating driver in 3D printing adoption. (IDEA Consult, AIT, VTT, CECIMO, 2016)

The empirical data from construction projects strengthens the existing knowledge that when 3D printing is applied in a project, it cannot be seen isolated from other technologies and systems. It requires a holistic perspective not only among designers, but from all common roles in the project. In its adoption process, it shows strong couplings to other digital technologies and enabling trends within and outside the construction industry, without which adoption is not be possible.

The explorative governance structure for 3D printing the majority of a building was partially already present in literature (IDEA Consult, AIT, VTT, CECIMO, 2016). This researched provides evidence that this scenario is indeed likely to be adopted in the future, and takes it one step further by introducing an industrial approach in which a large quantity houses are constructed with the same manufacturing process. This allows a visionary organization to recoup its additional investment for the first project. Furthermore, it complements the “what” with an explanation of the “why” and guidelines on the “how”.

Through collecting empirical data on real projects, a more realistic perspective was gained on the state of the art of 3D printing in a business context and its potential future role in the construction industry. In the initial desk research stages, lots of conflicting perspectives were found on the existing and potential role 3D printing would play in the construction industry. Media coverage on projects in which 3D printing was applied found in the initial desk research turned out to be misleading. Analysis of seven projects in which it was now applied and of the existing trends show that it is currently not ready for application in construction projects. Only one out of seven cases showed an application which was clearly competitive to traditional manufacturing methods (this was a plastic ornament). Regarding its potential future role, conferences presented clear visions how 3D printing would revolutionize the construction industry (Imprimer le monde, 3D printing conference Amsterdam, FABRICATE (Menges et al., 2017), exploratory interviews revealed the large amount of limitations that still exist, and scientific literature showed little consensus on the exact future development of 3D printing. (Jiang et al., 2017). This research coupled the conditions for 3D printing (based on empirical data of projects) adoption to existing trends, which ground the statement that 3D printing will be adopted in the future. Instead of revolutionizing the built environment however, it will be complement existing practice, and be competitive for specific applications in specific projects. Personally I think this will be in 2-5 years, once enabling trends are more mature.

The findings listed above provide awareness for project stakeholders considering to apply 3D printing in their project or develop related services or products, enabling them to make a more informed decision on whether to do so.

Limitations

A large portion of the cases that were studied was still in development, and its successful completion was not always evident. This means that the results of the observed governance could not be compared to the success of the overall project. This might have an influence on the reliability of the best practices that were selected. These were selected based on them solving a problem or utilizing an opportunity during the project, but might turn out to have negative side effects in a later stage in the project. An additional validation with the interviewees after the analyzed case studies are finished would increase thereliability.

The fact that the application in the case studies were generally not competitive to traditional manufacturing methods has an influence on how such a project is managed and therefore on the research results. The operationalized governance structure is therefore likely to need further refinement in the future when innovation is no longer required.

The majority of the selected interviewees were with people aiming to bring 3D printing into the market. This means that generally they have a positive perspective (and enthusiasm) for 3D printing in general. Their judgement therefore is subject to bias, in which positive aspects are emphasized during interviews and more negative aspects are not mentioned as much. This risk was mitigated by seeking consultations from a wide variety of project actors, including several critical engineers within Arup.

The case studies were analyzed from inception to construction, leaving out the operation and maintenance phases of the project lifecycle. Since long term performance of 3D printed objects is unknown, this constitutes an additional risk and role to be fulfilled when applying 3D printing in a project.

This research started by selecting case criteria, on basis of which generic statements were made on the future role of 3D printing in the construction industry. Characteristics outside of the selected criteria (material scale 3D printing, rectilinear 3D printing, renovation projects, research projects) are therefore limitedly incorporated in these generalized statements.

The complete operationalization of project governance was made during the interviews. This was because it was not yet clear where the problems lied exactly in the projects, and it was decided to keep the final outcome flexible until more information was gathered. As more knowledge was gained, better additional questions could be asked during interviews. This means that for the initial interviews, less specific additional questions could be asked, resulting in a less critical attitude on the answers provided by interviewees. Taking more time to fully operationalize governance before the commencement of the interviewees would have increased the reliability and depth of the research results. The risk this approach would have had however, is that the alignment of the research findings to existing knowledge gaps would reduce.

The governance domains (construction project, product design, innovation) were coupled to the conclusions at a late stage, after the validation phase. To compensate for this, the revised results were validated with Galjaard (a digital fabrication expert in Arup), who agreed on the results.

The suitability of the first designed governance structure for all individual case studies could not be guaranteed, due to unexpected logistical challenges. The initial plan for validation was to invite all case interviewees, 3D printing experts and project managers to validate the designed governance structure for components and provide additional input that reflected their individual cases. Unfortunately, the input from most case study interviewees was not obtained due to four last minute cancellations. Due to busy schedules and time considerations an additional meeting in which all be present could not be planned. To mitigate this setback, face to face validation interviews were planned with three interviewees (who were positive about the results and had limited comments), and digital fabrication experts in Arup (Shibo Ren and Salomé Galjaard). The latter introduces a limitation to the designed governance structure for 3D printed components, it is only valid when a small number of components is applied.

The second explorative governance structure was validated through the graduation committee, who did not show a consensus on the likelihood of its adoption. It was however validated in a business report from the European commission. Due to time considerations and its explorative nature for a future scenario further validation was not done.

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Appendix A Imprimer le monde 2017 Conference

This appendix presents key insights obtained during the Imprimer le monde Conference in Paris. After an introduction, the purpose of attending the conference is listed. Key insights per speaker are then presented in chapter 4, after which conclusions are given.

1 Introduction

Imprimer le monde is an exhibition currently being displayed in Centre de Pompidou, which demonstrates the possibilities by 3D printing. A wide variety of objects is placed at the exhibition, representing a wide variety of industries, as well as different disciplines like artists, architects, engineers, and researchers.

The exhibition had an opening conference on the 18th of march in which the creators of the exhibited pieces were invited to speak about their work. This was seen as an excellent opportunity to introduce myself to what 3D printing is all about. The conference included a lot of short presentations in which valuable insights were gained.

2 Purpose of attending the conference

The purpose of attending the conference was to get an initial general overview of the possibilities, applications and context of additive manufacturing. Several objects that were on display had a clear relation to the built environment, like printed concrete elements and digital fabrication methods by ETH-Zurich. The other interesting element was that the speakers came from different disciplines, which would provide different perspectives on how 3D printing would impact the built environment.

3 Program

The program as found on Centre de Pompidou's website is as follows:

Les formes du digital

Samedi 18 mars 2017

Keynotes

14h30-15h : Mario Carpo, professeur, Ecole Nationale supérieure d'architecture Paris-Malaquais, Paris et UCL Bartlett School of Architecture, Londres

15h-15h15 : Marie-Ange Brayer, conservatrice, chef du service Design et Prospective industrielle, MNAM-Cci, Centre Pompidou, Paris

15h15-15h30 : Christian Girard, architecte et professeur, Ecole Nationale supérieure d'architecture Paris-Malaquais, Paris

15h30-15h45 : Sophie Fétro, maître de conférences, Université Paris 1 Panthéon-Sorbonne, Paris

15h45-16h : Camille Bosqué, docteure et enseignante, Université Paris 1 Panthéon-Sorbonne,

Paris

Tables rondes

16h-17h15 : Table ronde - modérateur : Marie-Ange Brayer

Vincent Fournier, artiste et auteur, Paris

Yvan Gallet, fondateur d'Initial, groupe Gorgé, France

Catherine Gorgé, directrice de la division "Les Créations" d'Initial, groupe Gorgé,

France Claire Warnier et Dries Verbruggen, studio Unfold, designers, Anvers

Kevin Clément, docteur et architecte, Kengo Kuma and Associates, Université de Tokyo, Advanced Design Studies Unit

Michael Hansmeyer, architecte, programmeur, professeur invité Académie des Beaux-Arts de

Vienne Mathias Bengtsson, designer, Stockholm

Kieran Long, conservateur en chef, Victoria & Albert Museum, Londres

Pause

17h30-18h45 : Table ronde - modérateur : Christian Girard

Areti Markopoulou, architecte, directrice de l'IAAC (Institute for Advanced Architecture of Catalonia), Barcelone

Frédéric Vacher, directeur en charge de la prospective et de l'innovation ouverte, Dassault Systèmes, France

Fabio Gramazio, architecte, Gramazio Kohler Research, Zürich

Henriette Bier, architecte, enseignante, TU Delft University of Technology, Hyperbody Departement, Pays-Bas

Sina Mostafavi architecte, TU Delft University of Technology, Hyperbody Departement, Pays-

Bas Alisa Andrasek, architecte, professeur, RMIT Architecture and Design Melbourne

Lilian van Daal, designer, Arnhem

18h45-20h : Table ronde - modérateur : Justin McGuirk, Design Museum, Londres et Design Academy Eindhoven

Matthew Plummer-Fernandez, artiste, chercheur, Goldsmith College,

Londres Moreshin Allayari, artiste activiste, fondateur du collectif

Additivism, Berlin Daniel Rourke, artiste, critique, fondateur du collectif

Additivism, Berlin Emmanuel Cyriaque, directeur éditorial des éditions

YX

Goliath Dyèvre, designer, Paris

4 Key insights from speakers and table rounds

In this chapter key insights from several speakers are listed. Since not all presentations were relevant (like artists), only the insights relevant to the construction industry and the built environment were listed. It should be noted that through the translators it was not always so clear what exactly was said.

Mario Carpo

Through 3D modelling it is no longer required to translate a design into 2D drawings, but allows for direct communication of the design, without any filters.

Expects development of full 3D scanning (rather than 2D photography)

Christian Girard

Science fiction can become a reality: A future can be expected where we think a design, and can manufacture it directly through a coupling of AI, Big Data and neurosciences.

Sophie Fetro

AM already sees interesting applications in two main categories

- Manufacturing what can already be made (WinSun's printed villa's, IAAC's Minibuilders that print "out of the box")
- Thinking about new shapes with complex geometries. This latter category requires architects to explore varieties and new ways of working.

Camille Bosque

Digital manufacturing is quoted by the economist to be the third industrial revolution.

A democratization of technology id described, people can make their own customized products and are both creators as manufacturers.

Technology is in its initial stages now and is expected to grow, putting the architect at the heart of the design

First Roundtable (artists, designers, engineer)

Yvan Gallet (engineer)

Printing can be done in a wide variety of materials

- In art normally plastic is printed
- Alluminium, titanium and other ceramics are also possible

Printing is not plug and play, you have to manually polish and clean created products

Often the mistake is made that 3D printing can create any shape, but this is not the case

- Existing manufacturing constraints limit the freedom of form
- You might need to polish, paint, or apply treatment

3D Printing is not replacing other technologies, but can be used to create different characteristics

Dries Verbruggen (artist)

Materialise is an important player who's software is vastly used in the 3D printing industry

The relationship between client, designer and manufacturer will change

Authorship and IPR will become issues

- Digital designs can be easily slightly modified. What level of change is allowed to prevent copyright infringement?

Kevin Clement

Rather than replacing human labor, methods can be found to augment it

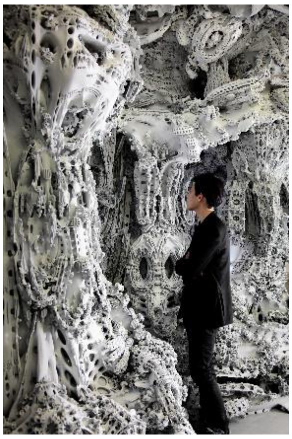
- They fabricated a pen which was able to build a tensegrity structure
- The pen is an integration of human labor and automation

Tensegrity is a great way to make light weight structures for engineers

- It is more flexible and it doesn't have to be as precise
- No projects on it yet but strong desire to do so

Michael Hansmeyer

Digital Grotesque demonstrates the complexity of from that can be achieved through 3D printing



- No cost for customization
- Low cost for complexity
- No limitations to shapes
- At some point they could manufacture more than they could design
- Coupling 3D printing with AI resulted in an algorithm that generated shapes of "infinite complexity"

Mathias Bengtsson, stockholm

Titanium table which shape was inspired by systems nature use to grow

- Based on a computational design of the growth of a plant
- Produced by electron beams to liquefy titanium powder

Questions round

It is a mistake to assume that anything can be printed

- You encounter different types of limitations (robotics, materials)
- Design for manufacture still applies, but now instead of human limitations it is the robotic and material capabilities that impose the limitations

People are not yet trained in the required professions for 3D printing

- There is a significant shortage of skilled workers

Printing is not economically feasible (yet)

- Expensive energy consumption
- The required machines are sophisticated and expensive
- From a designers perspective 3D printing is amazing, from an engineer perspective not so much, because you have to get it done within a certain timeframe and budget

Companies are now able to scan an object, digitalize it and build it, imperfection are however still present

Second roundtable (research groups)

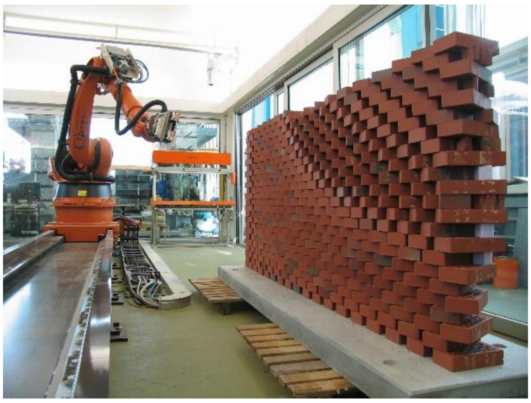
Material and IT research are important to bring 3D printing forward

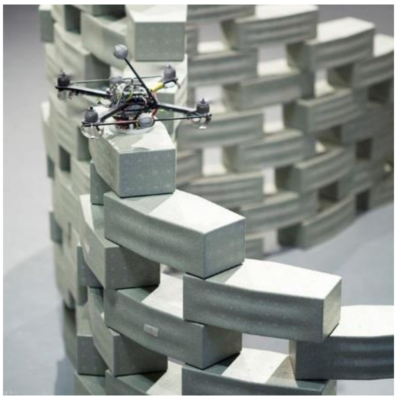
Fabio Gramazio (ETH Zurich)

3D printing is a subdomain of digital fabrication and the most radical way to do it

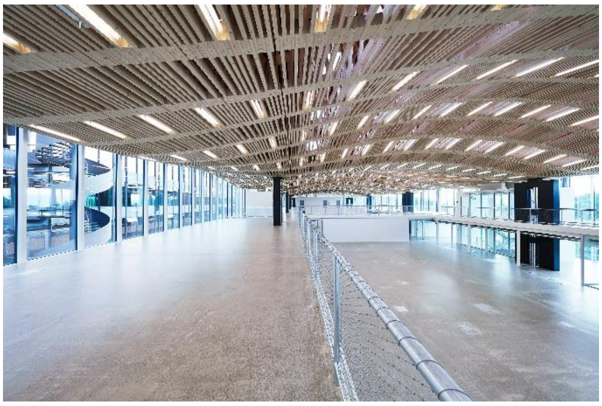
ETH Zurich is doing research with industrial robots and has developed interesting applications

- They have created a bricklaying robot (and a similar principle with drones)

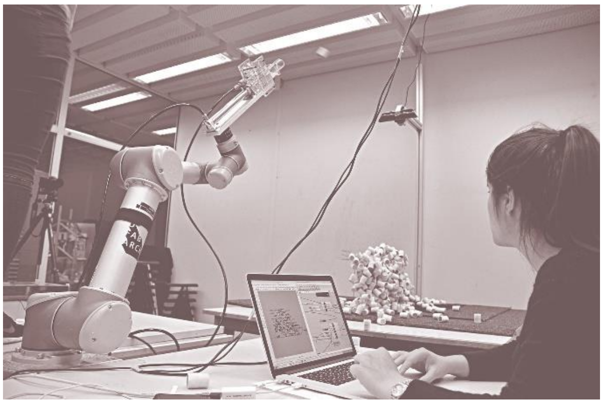




- They have fully digitally fabricated a roof structure in timber, which is currently applied in the Arch_Tec_Lab. According to Fabio, it didn't change price or time in this project.



- They have developed Smart Dynamic Casting (controlling parameters of process, through optimization the "perfect speed" of depositing material was found so that it is liquid enough to flow through the machine and solid enough to not collapse)
- Remote material deposition (throwing small pieces of material in the right place)



- Rock print (column printed only by string and gravel, fully digitally fabricated, no binder applied.


The main challenge is the applications of these innovations to actual construction

- Risks are more important in construction
- There is a lot of existing legislation
- Building has a long life-cycle

Alexandre Dubor (IAAC Barcelona)

IAAC has been working on a concept of a fleet of mini robots capable of printing out of the box (bigger than their own scale)

- Robot that prints the initial layer
- Robot that clamps onto this layer and prints the wall
- Robot that
- Lot of research is still required to develop it further


Terra performa has shown to be capable of printing structures with earth (local material) using a extrusion nozzle suspended by cables

WASP has demonstrated to build on site structures with clay

Frederic Vacher

Buildings have to meet more requirements than conventional products

- They have to be stable, stiff and strong
- They have to be sustainable

There is a misconception that robots will completely take over. Rather, they will complement human labor.

Henriette Bier

It is possible to topologically optimize your material, so you only place material where needed

- This could be among others done structurally, acoustically, and for thermal performance

TU Delft its developing multimode hybrid processes, in which humans and robots are working together

- Integrating humans and robotics
- Combining additive and subtractive processes
- Future outlook is incorporating multiple functional requirements

Buildings are complex systems with different components made of different materials, which have to perform different functions at different times.

Lillian van Daal

3D printing can be coupled with bio mimicry

- 3D printing allows to create the complex shapes found in nature

(engineering) Inspiration for buildings can be drawn from nature

5 Conclusion

The conference was a great initial start to get acquainted with the topic. The most important insights are listed in the bullets below.

3D printing is a wide field of study

- It has a wide variety of applications, also in the construction industry
- It is part of (and closely related to) the wider family of digital fabrication, which also includes subtractive and hybrid methods.

- 3D printing technology in the built environment is a topic of active research
- Printing can be done in a wide variety of materials and can be done with different technologies

3D printing has a strong coupling with design, which in turn leads to potential coupling to other fields of study and technologies

- High complex shapes can be realized by 3D printing
- This means it now makes sense to functionally optimize designs, leading to a new field of study.
- The design can be coupled to other fields, like bio mimicry, algorithmic design, AI, machine learning.

3D printing has a lot of potential

- Automation can be introduced in the fabrication process
- Designs can be functionally optimized
- Material is only put where needed

Though possibilities are large, there are still limitations

- Robotic and material capabilities impose limitations on the freedom of form that can be realized
- Materials and printers are expensive (also in energy consumption)
- People do not yet possess skills to utilize the opportunities
- The technology is in its initial stages

Appendix B 3D Printing Conference Amsterdam 2017

This appendix presents key insights obtained during the 3D Printing Conference 2017 in Amsterdam. After an introduction, the purpose of attending the conference is listed. Key insights per speaker are then presented in chapter 3, after which conclusions are given in chapter 4.

1 Introduction

The 3D printing conference 2017 in Amsterdam is an exclusive conference around the business impact of additive manufacturing & 3D Printing. Several leading companies and researchers present their insights on the current state of Additive manufacturing and what next steps can be expected in its future development. The following passages are quoted from the conference's website:

"Engage in the 3rd edition of this premium event around the business impact of additive manufacturing & 3D printing. The 3D Print market is maturing fast and we see investments in the digital manufacturing world growing in 2017. Also there is a focus on industrial end user parts. The attendees of this focused invitation only event are leading the digital transformation of their companies.

Visitors of the 3D-Print Conference Amsterdam 2017 learn all about how 3D printing is already changing global economies, value chains, product development cycles, distribution chains, transform our industries and, ultimately how it will change our way of life. Exciting and inspiring speakers from companies that provide cutting edge smart technologies and from institutes who have all the latest insights will take them into the future and shine their light on what's going to happen next and how companies get on board."

2 Purpose of attending the conference

The purpose of attending this event was to obtain input for the future outlook of the design process this research aims to develop. As can be seen in the list of speakers, the speakers are leaders in their industry and research fields, their industries are in turn are several years ahead of the construction industry. Gaining insight in their perspectives on the future of AM therefore provides valuable input on a potential development of the designed process in this research.


TRANSFORMING INDUSTRIES & THE FUTURE OF 3D PRINTING

13:15pm - 13:45pm | Entrance & Foyer |
COFFEE & REGISTRATION

13:45pm - 13:55pm | Studio B
OPENING 3D-PRINT CONFERENCE AMSTERDAM 2017
Chairman: Herman van Bolhuis - Director of ASSEMBL3D and the 3D Makers Zone Amsterdam Metropolitan Area

13:55pm - 14:25pm | Studio B
THE FUTURE OF ADDITIVE MANUFACTURING: A DELPHI STUDY ON ECONOMIC AND SOCIETAL IMPLICATIONS OF 3D PRINTING FOR 2030
Frank Piller - Professor management and scholar of mass customization & open innovation, University of Aachen (Germany) & Co-director of the MIT Smart Customization Group

14:30pm - 15:00pm | Studio B
THE AM JOURNEY FROM ANALOG TO DIGITAL WITHIN HP INC
Clara Remacha - Customer & Market Development HP Inc

15:05pm - 15:25pm | Studio B
SECURED INDUSTRIAL MANUFACTURING: BUILDING A DISTRIBUTED GLOBAL FACTORY THAT DELIVERS PRODUCTS WHEN AND WHERE NEEDED, WHILE PROTECTING ALL STAKEHOLDERS' RIGHTS
Brant Richards - CEO Genesis of Things

15:25pm - 15:45pm | Studio B
FINDING THE BUSINESS CASE: THE MAIN DRIVERS FOR THE ADOPTION OF METAL ADDITIVE MANUFACTURING
Onno Ponfoort - Practice leader 3D Printing, Berenschot
Luuk Nolet -TU Twente, intern at Berenschot

15:45pm - 16:00pm | Foyer | BREAK

16:00pm - 16:20pm | Studio B
MECHANICAL METAMATERIALS:
NEW POSSIBILITIES WITH COMPLEX STRUCTURES
Prof. Dr. Martin van Hecke - Professor Dr. in Biological & Soft Matter Physics - Leiden Institute of Physics and group leader at the FOM Institute AMOLF in Amsterdam

16:20pm - 16:40pm | Studio B
POSSIBILITIES AND FUTURE APPLICATIONS FOR 3D-PRINTING AND INFRASTRUCTURE.
Dr. Ir Wesse Wits - Assistant Professor "Physics in Design" at Laboratory of Design, Production and Management at the Faculty of Engineering Technology, University of Twente

16:40pm - 17:00pm | Studio B
AUGMENTING FABRICATION AND WIRE AND ARC ADDITIVE MANUFACTURING IN THE BUILT ENVIRONMENT.
Dr. Ir. Jouke Verlinden - Assistant Professor Computer Aided Design Engineering | Chair ODC-IO | Industrial Design Engineering at TU Delft

17:00pm - 17:30pm | Studio B
INTERACTIVE PANEL DISCUSSION:
WHAT IS TO COME FOR INFRASTRUCTURE WITH 3D AND 4D PRINTING?
Prof. Dr. Martin van Hecke - Professor Dr. in Biological & Soft Matter Physics - Leiden Institute of Physics and group leader at the FOM Institute AMOLF in Amsterdam
Dr. Ir. Jouke Verlinden - Assistant Professor Computer Aided Design Engineering | Chair ODC-IO | Industrial Design Engineering at TU Delft
Dr. Ir Wessel Wits - Assistant Professor "Physics in Design" at Laboratory of Design, Production and Management at the Faculty of Engineering Technology, University of Twente

17:30pm - 18:45pm | Terrace & Foyer |
DRINKS & NETWORKING

18:45pm - 21:00pm | Studio A
EXCLUSIVE NETWORKING DINNER

FIGUUR 1 PROGRAM AND SPEAKERS

3 Key insights per speaker

This chapter provides an overview of the key insights in the presentations from all speakers, from the perspective of likely future developments for additive manufacturing. For more detailed information on the speakers, the website can be consulted.

The future of additive manufacturing: A Delphi study on economic and societal implications of 3D printing in 2030, by Frank Piller

- How we think about something determines how we manage it
- It is likely that the stage-gate model for manufacturing will change

Existing innovation strategies are ill-equipped to deal with additive manufacturing and other digital transformation technologies

- At the moment businesses often try to structure innovation in a stage-gate process, but technology is allowing us to increase the amount of iterations and producing small end-results, meaning that all stages are gone through at the same time. Processes that are more suitable than the stage-gate process are agile/design thinking/lean startup processes.
- Creating centralized corporate strategies does not work, because they are too slow. Better to facilitate small in-house teams and then sharing it through the company.
- Open-source consumer communities can be faster than large traditional companies, because they have the data available and don't need the traditional procedures of large established companies. (diabetes case)

Innovation is a continuous and unpredictable process in which it is hard to predict who ultimately benefits.

- Innovation does not stop at the usage phase, it starts there. For example, companies are currently focused on creating platforms like AirBnB and Uber, but don't realize that as soon as the platform is created a larger ecosystem around it starts to develop.
- Often "Silicon valley" players join in at this moment and capture the value from this ecosystem, leaving the creator of the platform behind.

There are strong ties between additive manufacturing and other digital transformation technologies

- Additive manufacturing is a key technology and an aspect of a wide variety of digital transformation technologies, the paths of market entry show similar patterns.
- The real value comes when integrating digital transformation technologies, one cannot be seen isolated from the other.

There is a lot of uncertainty regarding the future development of additive manufacturing.

- The strong ties to other technologies increases both the potential as the amount of uncertainty around future development paths.
- Comment from after the speech: Often people reach consensus as the end of a Delphi study, but in this case the final result still showed a wide variety of opinions.
- "Think like an app, instead of a platform"

The AM Journey from analog to digital within HP Inc, by Clara Remacha

The adaptation of AM can be compared to a marathon.

- It is a long continuous process in which it is very hard to win
- You cannot win alone (coopetition)
- Pace setters (which HP aims to be)
- How well the extra's are done determines the winner (which HP intends to execute)

HP expects 3D printing will compete with traditional manufacturing methods in the manufacturing market in the future

- Currently 3D Printing represents a very small percentage of the total manufacturing market and is primarily applied in the prototyping stage of new products. HP expects that the applications will move towards production of end-products, which constitutes a 12 trillion dollar market.

HP wants to be a pacesetter in this process

- They have developed Jet fusion technology for their printers, providing multimaterial print possibilities and opportunities to recycle a large percentage of the waste material.
- They are aiming to cut on material cost (currently 70% of the total cost) by creating an open platform and partnering with material suppliers.
- The currently focus on plastics, and potentially move towards other materials later.

HP see's clear benefits in 3D printing compared to traditional manufacturing methods

- Traditional manufacturing uses molds, which have to be adapted when a customer changes its requirements. This takes time and costs money.
- Lead time (time to market) of new products could be reduced by removing the need for a mold and producing the end-product directly.
- Part consolidation reduces assembly cost and reduces the amount of weak (assembly) points.
- It allows for personalized product

Certain things need to change in order for 3D printing to become widely adopted

- Quality control procedures need to be made
- Designers have to overcome their limited perspectives
- Software tools need to change
- Product lifecycle needs to make a transition from prototyping to production.

There are multiple business models available for 3D printing to develop

- In the future there could be (centralized) production farms in which printers are installed to produce products
- Consumers could also buy HP's printers to produce their products at home (decentralized).
- HP does not see these as mutually exclusive, but rather going hand in hand.

Securing industrial manufacturing: building a distributed global factory that delivers products when and where needed, while protecting all stakeholders' rights, by Brant Richards

There are several technology induced mega-trends

- Increased transparency. Brant goes so far as to say that privacy is dead.
- Decentralization
- Radical technology convergence, creating lots of possibilities AND uncertainty.

The transition in application from prototyping to production is expected

- General Electric (GE) and Siemens are investing billions of dollars in R&D for 3D printing.
- Leading players like HP are investing too

Difficulties exist that are hampering the adoption process

- Cost of machine and materials
- Trust, how can you verify where the file was produced? How do you know it is safe to use?

- Quality, how do you know it was manufactured by a certified organization?
- Production repeatability

GoT aims to making 3D printing accessible to all, by coupling 3D printing with other disruptive digital technologies

- Blockchain and Internet of Things can be used for quality control
- Tagging products, including chips to track life-cycle performance, providing a digital product memory.
- Smart contracts through cryptocurrencices (distributing money to the right people as soon as the product is created)
- Provides a digital, open online platform + ecosystem for additive manucturing.

An interesting process for such a platform could be the following:

1. Define virtual product (either download a file or create it yourself)
2. Virtual testing and validation (to make sure it is printable)
3. Storing the file in a distributed way in an interplanetary file system.
4. Selecting the best printer for your product (based on meta-data to ensure privacy)
5. Creating a smart contract between manufacturer and customer
6. Transfer file to the printer (like a snapchat, it gets deleted after production)
7. Production (while IoT sensors ensure the quality)
8. Tagging product with a chip, providing an (updatable) digital product memory for the whole product lifecycle.
9. Sharing this on a blockchain to continuously authorize and validate the quality of the product.

Usage of crypto currencies is expected to rise in the future and can be suitable for this business model

- A cryptocurrency produces Coins or Tokens, which represent programmable content. An example is Bitcoin.
- Cryptocurrencies allow for smart contracts to be developed where the payments are directly distributed to the relevant organizations after duties in the contract are performed
- Cryptocurrencies are receiving a lot of attention currently. Bancor did an ICO (Initial Coin Offering) one week ago in which a new token or coin is released and attracted capital. This ICO raised 140 million dollars in capital in less than an hour.

Focus is currently on industrial applications and developing a golden standard, later develop into consumer markets.

Finding the businesscase: the main drivers for adoption of metal additive manufacturing, by Onno Ponfoort and Luuk Nolet

3D Printing is not only an adoption question, but also awareness, which is still not completely there yet.

If we are honest, the advantages often mentioned, are currently also hurdles in the adoption of AM

Advantage/Opportunity	Hurdles/Challenges
Lower cost	Material is still expensive, production cost/part are relatively high
Better design	New design rules and guidelines have to be adopted. Not all engineers are capable of doing that (yet).
Customization	Customization requires a business case that is feasible (demand for the degree of customization 3D Printing can offer)

Sustainability	Might be good over the whole lifecycle, but the machines still consume a lot of energy
New business models	Little awareness still in larger value chains. In small niches it is starting to grow, but larger value chains are still very hard to penetrate.

- Relative growth has declined in the last year (26% in 2015, 17,4% in 2016), due to the fact that the two biggest 3D printing system companies were not able to maintain their growth line.

Companies who have adopted AM can be characterized as visionary leaders, with room to maneuver, and willing to step in

Reasons for adopting:

- Technical
    - Relative advantage (achieving a functionality which you can normally not achieve)
- Organizational
    - Centralization (a body that is happy to make the decision and grow)
    - Organizational Slack (there is room to improve/maneuver and to make mistakes)
    - Organizational image (being a frontrunner in society)
- Environmental
    - Pressure from competition (we want to stay ahead of competition)
    - Supplying market activities (suppliers who are able to have a discussion with their potential customers about possibilities of 3D Printing)

Recommendations for adopters

- Assessing the drive and enthusiasm of bodies within the organization might be a very important element.
- If you want to adopt, pay good attention to your business case.

Companies who have not adopted AM can be characterized as cautious managers, with internal investment guidelines, looking for risk reduction

Reasons for not adopting:

- Technical
    - Complexity (it is not easy to adopt 3D printing)
    - Cost (a large investment is required)
- Organizational
    - Slack (less room to maneuver)
    - Business case (is difficult to do)
- Environmental
    - Pressure from business partners (a lack of it)
    - Pressure from competition (a lack of it)

Recommendations for approaching non-adopters:

- Showcase real life cases, where you see the end-result.
- Involve supply chain partners, spreading the risk to all partners.

There are six buying roles, which help to identify which customer should be approached first in the adoption process

- Designer

- Influencer
- Initiator
- User
- Purchaser
- Gatekeeper

How can we make sure that companies who should adopt are actually adopting, how do we make sure that companies who should not adopt will not adopt the technology. This is a current topic of interest in the economic and business world.

- Investment decision: Stay ahead of the curve, but you need room for investing in it

The technology does not seem to be there yet (at this moment in time)

- There were several examples of companies who adopted but where it would have been better if they would not have adopted.
- Companies that didn't adopt often made the right decision to do so.
- Companies have to pay a rather high price for a technology that has not yet proven to be successful, it takes a specific type of organization to be willing to do that.

Mechanical Metamaterials: new possibilities with complex structures, by Prof. Dr. Martin van Hecke

Most materials don't exist yet

Material (mechanical) properties can be influenced by changing their structure

- "Impossible properties" can be created, like increasing thickness when it stretches. Another example is influencing stress strain relationships (decreasing internal stresses by increasing force)
- Applying a certain force leads to a specific (programmable) change in shape.
- Possible applications are foldable structures

3D printing can utilize the applications of meta materials can be utilized, because 3D printing allows highly complex shapes to be created, which 3D printing is capable of

This could have interesting applications for the construction industry

- Materials and structures can be developed that react in differently in different situations. This reaction can be programmed and designed allowing for multimode materials.
- Properties can be made through a few base materials (which also removes the need for printing in multiple materials), the desired properties can be designed by adjusting the structure (locally).

Possibilities and future applications for 3D-printing and infrastructure, by Dr. Ir Wesse Wits

In the development of new technologies, the engineer is the bridge between the physicist and the business model.

Complex (freeform) 3D printed objects have many applications which provide opportunities

- Influencing fluid flow in multiple directions
- Shape optimization for function
- Materials can be optimized locally (only putting expensive material where needed, the involved discipline is primarily chemical engineering)
- Machines that integrate additive and subtractive processes already exist

Before the opportunities can be utilized, we are in need of additional training

- Geometry (topological optimization)
- Processes (how do we combine additive with subtractive?)
- Materials
- Thinking across disciplines, industries and scales.

Where traditionally manufacturing runs behind designers, currently it is the opposite

- Existing design software does not allow for the functional optimization required to fully utilize the benefits enabled by freeform production.

Augmented fabrication and wire and arc additive manufacturing in the built environment, by Dr. Ir. Jouke Verlinden

There is an often encountered perspective that generative design will put designers out of work

Time for digital fabrication is very exciting

- Coupling with computational design (using AI, machine learning to generate design structures)
- How to include the human in the loop so that it does not become a lights out factory?

The Boston conference had interesting speakers present

- Matthias Kohler from architecture
- Skylar Tibbits on self-assembly
- Scott Hudson (computer-human interfaces)

Augmented fabrication puts humans back in the design loop, as humans still have value to deliver in the process

- Emphasize with product and consumer
- They are good at spatial reasoning (what something looks like and could look like)
- Communication with stakeholders (augmented reality in conceptual prototyping stage)
- Little researched field

Using Augmented Reality in stakeholder communication provides an interesting opportunity

- Communicate building with hololens for example. The information on cost, time, LCA is automatically generated for a particular alternative that its discussed with a stakeholder.

4 Conclusion

The conference gave valuable new insights in the business case of 3D printing. It also provided valuable input for the future outlook, because the speakers are leaders in their respective industries, which in turn are several years ahead of the more conservative construction industry and have higher R&D budgets. The conclusions presented below are related to this future outlook.

The adoption process of 3D printing shows similar principles to other digital transformation technologies

Besides big potential, the future of 3D printing has a lot of uncertainty

- The technology can be coupled to other digital transformation technologies. Couplings are possible with:
  - Blockchain (smart contracts & verification of origins)
  - IoT (digital product memory, on-site quality control)
  - Cloud computing (online platforms allowing clients to find the right printer)
  - AI & Machine Learning (generative design)
  - Augmented Reality (designs can be virtually communicated directly to stakeholders)
  - Creation of new materials (which mechanical properties can be designed)

- A Delphi study usually reaches consensus, but in the future development study from Piller consensus among experts was not reached.

Innovation doesn't stop when a product is created, but starts when it's created

- A lot of companies are currently focused on creating platforms and see this as the final goal, and are surprised when a whole ecosystem develops around it
- Silicon Valley players often come into the picture at this point and capture the value of this system, because they understand data

Existing corporate cultures are ill-equipped for the adoption of 3D printing

- They are slower and use a stage-gate process, where agile/lean startup/design thinking approaches are more suitable for the adoption digital transformation
- They centralize strategies, where it is better to facilitate small in-house (driven) teams and sharing it throughout the company
- People do not possess the skills required for 3D printing

The transition towards end-product manufacturing has huge (business) potential

- The manufacturing industry represents a 12 trillion dollar market
- So far 3D printing was primily used for rapid prototyping, which represents a very small percentage of this market.
- HP, an industry leader, expects a transition from rapid protytoping to manufacturing, where the big market share is.

Multiple business models are possible

- Centralized printing farms replacing existing factories
- Consumers having their own printers

Insights heard at this conference confirm the view that the innovation is currently in the early adopter stage and is expected to move to the early majority stage

- A lot of companies are currently evaluating their investment decision in adopting 3D printing. Investing now is costly and complex, but could realize significant benefits in the future.
- A big player like HP expects 3D Printing to be adopted into the mainstream manufacturing market.
-

The technology does not seem to be there yet

- A critical look on the topic reveals that the significant challenges can be grouped in the same categories as the opportunities so often described by 3D printing enthusiasts.
- Growth has declined last year (relatively)
- Onno Ponfoort (involved for 13 years in the industry) claims that a lot of the interviewed companies for Berenschot's research that did not invest in the technology, were right to do so.

3D printing in the future does not have to be a "lights out factory"

- There is still a role for humans in the design process, potentially through augmented reality.

Appendix C Interview 3D-Printing in the Circular City" Project (Foteini Setaki)

This appendix presents the results of the interview conducted with Foteini Setaki on the 3D-Printing in the Circular City" Project.

1. General questions

This part contains general questions on lifecycle phases, involved actors, and identified activity themes per phase.

Life cycle phases
In a traditional Dutch project, several phases can be identified. For the manufacturing of a 3D Printed (3DP) element, the Aerospace industry suggests the following phases. Please state if the phases are applicable to your project, and if not, which phases could be identified.

Lifecycle Phases Construction Project	Applicable? (check box if applicable)
Initiative/Feasibility	x
Project Definition	x
Design (VO, DO, TO)	
Tendering	
Execution Design (UO)	
Construction	
Usage/exploitation	
Other:	Materials, Applications, Printing, Future applications

Note: Materials and applications could be characterized as initiative/feasibility and project definition. The actual printing can be described by the phases below.

Phases 3D printed Element	Applicable? (check box if applicable)
Computer Aided Design	x
Preparation of Geometry for 3DP	x
Machine Setup	x
Manufacture	x
Cleaning and Finishing	(only for last prototype)
Other:	Going through process multiple times

Note: the phases Computer Aided Design (CAD) until manufacturing were gone through multiple times. The actual cleaning and finishing was done for the last prototype.

1. In which of these phases were you involved?

All phases

2. In which phase was decided that 3DP would be used?

Initiative. The 3D-Printing in the Circular City" project is a research Project. A goal for the research was to investigate the potential application of 3D printing for plastic waste material.

3. What was the motivation for using 3D printing?

The goal of the research was to investigate potential applicability of 3D printing. Another motivation of investigating 3DP was the potential to add value to discarded materials (which could be used again with 3DP).

Actors
In a traditional construction project, several standard actors can be identified. 3D Printing could introduce new actors in the process. Examples are mentioned below

4. Which actors were present in your project?

Standard Actors	**Applicable? (check box if applicable)**
Client(s)	X (AMS + Municipality)
Architectural Firm	X (Aectual/DUS Architects)
Engineering Firm	(researcher experience was sufficient)
Contractor	
Subcontractor	
Other advisors (e.a. Project Manager)	
Investors	X (AEB, AMS)
Other:	
Potential new Actors	
Software suppliers	X (few existing softwares used)
3DP System suppliers	X (DUS Architects)
Material supplier	X (Recycling agency, AEB)
3DP Consultancy	(researcher experience was sufficient)
Service Providers	
Other:	

5. What were the roles of the involved actors?

DUS Architectures & Aectual (startup)

- Architectural firm
- In possession of printer
- Actively involved in recycling plastic waste into 3D printing material
- Printing, aided in material development process

AEB

- Burning material to produce new energy
- Produce statistics on waste that Amsterdam throws away
- Brought into contact with Sita, plastic separation company.
- Give insight on waste problem in Amsterdam
- Contributing financially, (they were interested in adding value to material that currently has no value)

AMS Institute

- Research institute. TU Delft, MIT, Wageningen university partnership. Work with local authorities, private companies, and research groups. Secure financing and distribute to research projects. Agenda in circular economy
- Financed the project, "Project sponsor". They helped with communication with and promotion of the project to the municipality. There were monitoring the Monitoring but not intervening

- Involved in meetings but did not actively steer the project

TU Delft

- Facilitating laboratory for tensile strength tests
- Took care of the administration (finances)

The New Raw (Foteini)

- Startup, interested in circularity role.
- Designed the geometry
- Material development process
- Coordinated the process

6. Do you know if there were any contracts installed between the involved actors? If so, between which actors?

No contracts were installed. However, a letter of intent to apply for the funding was created.

Project activities

Activity Themes	**Applicable? (check box if applicable)**
Client themes	
Client actions	X (meetings for funding)
Contracts	
Program of requirements	X (small project)
Other:	
Design themes	
Architectural Design	
Interior	
Landscape	
Building physics & Acoustics	
Structural/Civil	X (designing geometry so it can take load)
Installations	
Geotechnical	
Design integration	X (ensuring printability of the virtual model)
Other:	(product design, detailing (for horizontal adhesion horizontal)
Project Management Themes	
Organization/process integration	X
Information/communication	X
Risk management	
Other:	

7. Can similar themes be identified for the project phases you mentioned? If not, what themes existed in the project?

Applicability of the existing themes is limited, because the goal is a product as opposed to a building. Additional themes included the product design and detailing. The latter entails ensuring the horizontal adhesion within one layer (not too narrow and not too wide I><I) to ensure a printed final product.

8. Which themes required the most attention?

Challenge was making a geometry that could be printed.

9. Was communication ad-hoc or planned?

Ad-hoc. Several meetings, every three months with consortium.

10. Was there a project manager installed to coordinate the process? If not, who coordinated the process in the project?

The project was on a small scale, therefore no project manager was required. The coordinating roles were taken by Setaki.

2. Specific questions per lifecycle phase

This part contains specific questions on the key activities in each phase and which organizations were responsibility for it.

11. What was the goal and the key activities of each stage that was previously mentioned?

1 Materials

Goal: Finding a suitable material for the project and gain knowledge on its properties.

Key activities:

- Literature study (who did something similar)
- Extruding tests with several waste materials (gain knowledge on printability)
- Strength validation (laser cutting plates, tensile stress tests, comparing with original material)
- Consultations material expert from recycling industry (adding fibers for better finishing)

2 Applications

Goal: Investigate where 3D printed objects could be useful in the built environment of Amsterdam.

Key activities:

- Brainstorming session with consortium + municipality
- Deciding on product to be printed (a bench was considered to be the best option)

3 3D Printing

Goal: Manufacturing a 3D Printed Bench with the selected material

Key activities[11]:

a) **Computer Aided Design**

[11] The following subphases (a-d) were done in an iterative fashion. A virtual model was printed, then feedback was obtained on the printability, this knowledge was then incorporated in the design again. The whole process of iterations took about a month. The experience of DUS architects helped to increase the speed of the process.

- Creating a virtual parametric model of a bench in an existing software
  - Taking into account requirements like ergonomics (has to be a chair), customization possibilities (height profile, length, and potential of writing on it)
  - Taking into account boundary conditions like printability (inclination angle, printing path, strength of product)
  - Incorporating feedback from manufacturing process observations

b) Preparing Geometry for Printing

- Translating the virtual parametric model into a software that is understood by the printer (STL, Zipcode)
- Sending the file to the party who prints the design

c) Machine Setup

- Reserving the printer (little availability)
- Ensure power for the 3D printer
- Last minute checks

d) Manufacturing

- Monitoring progress and note observations
- Printing part of the product
- Testing structural integrity
- Print final product (if strength seems sufficient)

e) Cleaning and Finishing

- Polishing
- Checking for integrity (quality control)

4 Future applications

Goal: Exploring potential future applications for this way of recycling plastic waste in the city of Amsterdam

12. Which actors were responsible for and contributing to these activities? (RASCI)[12]

Key Activity	Aectual/DUS	AEB	The New Raw	AMS Institute	Municipality	TU Delft

[12] RASCI is a method to clarify the responsibilities for activities within a project. R = Responsible (verantwoordelijk), A = Accountable (aansprakelijk), S = Supporting (Steunen), C = Consulted (raadplegen), I = informed (informeren).

Literature study (who did something similar)			A			
Extruding tests with several waste materials (gain knowledge on printability)	R	S	A			
Strength validation (laser cutting plates, tensile stress tests, comparing with original material)			A			S
Consultations material expert from recycling industry (adding fibers for better finishing)	S		A			
Brainstorming session with Municipality	S		A	S	S	
Deciding on product to be printed	S	S	R	S	S	
Creating a virtual parametric model of a bench in rhino (grasshopper)	S		A			
Translating the virtual parametric model into a file that is understood by the printer (STL, Zipcode)	R		S			
Sending the file to the party who owns the printer			R			
Reserving the printer	R		I			
Ensure power for the 3D printer	A					
Last minute checks	A		S			
Monitoring progress and note observations	R		I			
Printing part of the product	R		I			
Testing structural integrity	S		R			
Print final product (if strength seems sufficient	R		S			
Cleaning and finishing of Product	R		S			

3. Challenges

13. Can you give examples of organizational challenges that were encountered during the project? How did you deal with these?

There were no organizational challenges, potentially due to the small scale of the project.

14. How did you verify the strength/stiffness and stability of the structure?

Laboratory of TU Delft, testing material property testing. Layer orientation played a role in the strength of the material. Based on these results, a bench was designed. The strength-testing of the whole object will be done when it will be placed in public space, in September.

15. What was the method of financing for the project (gift, co-financing, public funding, private investment)

Co-financing: funding from AMS and private investment from AEB. Also several in kind-contributions in the form of consultations from organizations.

4. Concluding questions

16. How do you think the process could have improved?

Involve the municipality (client for end product) earlier in the process.

Having a 3D printer available can speed up the process. The printer at DUS had to be reserved which sometime was a bottleneck in the process.

Appendix D Interview de Vergaderfabriek (Hugo Jager)

This appendix presents the results of the interview conducted with Hugo Jager on the Vergaderfabriek project.

1. Introduction

Interviewee
Hugo Jager is originally an economist, and has been occupied with economical and strategic problems related to innovations and their implementation in organizations. He is a partner at Revelating.

Revelating provides consultancy services related to creating awareness of a technology, enter the market at the right time, and developing applications for it. This results in an application that is ahead of the competition and therefore the organization can benefit longer from the innovation and realize a competitive advantage.

Does this mean that your services are normally related to organizations and now a transition is made to projects?

The question is no different. Managing different company goals in the same project makes it more complex, but the question on how to realize it remains the same. In companies you also have departments with leads, having their own culture, etc. What is needed In both organizations and projects is a client with a clear goal and vision and an architecture which allows individual companies/departments to achieve its goals. If this is not the case, a project is likely not to be successful.

This is particularly relevant for a project like the Vergaderfabriek because the risks are high. In a developed technology a client takes on board a project developer who then takes the client through the value chain step by step. If the whole chain still has to become familiar with the technology however, they also have to be educated on it. Revelating can provide an added value here by educating the people involved in the value chain on a new way of thinking.

2. General questions

This part contains general questions on lifecycle phases, involved actors, and identified activity themes per phase.

Life cycle phases
In a traditional Dutch project, several phases can be identified. For the manufacturing of a 3DP element, the phases below can be identified (model based on Aerospace Industry). Please state if the phases are applicable to your project, and if not, which phases could be identified.

Lifecycle Phases Construction Project	Applicable? (check box if applicable)
Initiative/Feasibility	X
Project Definition	X
Procurement	X
Design (VO, DO, TO)	X (VO in development)
Execution Design (UO)	
Construction	
Usage/exploitation	
Other:	X (Hackathon – after project definition)

VO is in development. VO has now gone through three iterations.

Phases 3D printed Element	Applicable? (check box if applicable)
System Development	
Computer Aided Design (CAD)	X
Preparing the CAD for Printing	
Machine Setup	
Manufacture	
Cleaning and Finishing	
Verifying structural integrity	
Assembly	
Transport	
Other:	X Printing strategy

Phases within the VO are not applicable to the iterations described in the system development model. The primary instrument used is the whiteboard (with sketches) and the integration between the various disciplines. (inclination angles, point of gravity, one-print or multi component print). This phase could be referred to as developing a printing strategy (inquiring on knowns and unknowns; what are capabilities of material, what can we verify structurally). Input is delivered from the disciplines in the consortium team (Architect, Installations, Contractor, Structural Engineer, CyBe), which are then discussed with the other design team members. The process has a diverging nature and aims to integrate functions while generating design alternatives on a general level. A computer aided design (CAD) came as a result of one of these alternatives and is at the moment undergoing structural calculations.

1. In which of these phases were you involved?

All phases from project initiation. Important role in initiative, program of requirements, and advising during procurement. During the VO phases, Revelating is primarily facilitating the parallel processes between the TU/E, Gemeente Voorst and verifying that the VO is aligned with the program of requirements created by the client. He does not have a role as architect or structural engineer.

2. In which phase was decided that 3DP would be used?

In the initiative phase.

3. What was the motivation for using 3D printing

First reason was that the client was very enthusiastic about the 3D printing technology. Second, the client wanted an iconic, sustainable, meeting location. The client also wanted to use sensing & sound to enhance the experience of the meetings. A 3D printed building suited this digital image.

Actors
In a traditional project, several standard actors can be identified. 3D Printing could introduce new actors in the process. Examples are mentioned below.

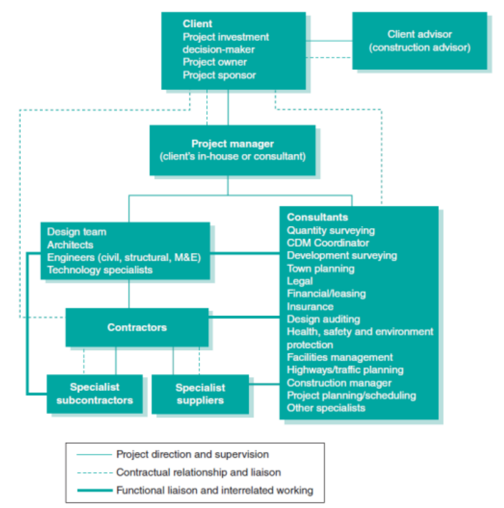


Figure 3.2 Typical project team structure.

4. Which one of these actors was present in your Project?

Actors	**Applicable? (check box if applicable)**
Client	x (Slaapfabriek)
Architect	x (Pim van Wylick, the Form Foundation)
Engineer	X (W&B - structural, Engie - installations)
Contractor	X (Van Wijnen)
Subcontractor	
Specialist consultants (i.e. Project Manager)	X (Lexence Advocaten – legal support)
Other:	X (Gemeente Voorst – permit provider)
	X (TU Eindhoven, material developemnt and verification of structural integrity)
	X (Centre4moods, sensing technology)
Potential new actors	
Service Providers (delivers printed objects)	X (CyBe)
3DP System supplier	
Software supplier	
Material supplier	
Other:	X Revelating (process facilitator)

5. What were the roles of the involved actors?

The Form Foundation (TFF)
Architect. Winner of the Dutch Hackathon in May 2016 together with CyBe. Has a role during the Hackathon and VO stage of the building.

Witteveen&Bos (W&B)
Engineering firm. Is the structural engineer in the VO stage.

CyBe
3DP service provider. Engineering and printing of Concrete elements. Their role is related to the engineering and delivery of concrete elements.

Van Wijnen (VW)
Company that builds dwellings. This is the contractor in the project and is involved in the VO stage.

Engie (EN)
Dutch supplier of green energy and gas. Responsible for the installations during VO stage.

TU/E (TUE)
TU/E is a technical university conducting research on 3D Printing. They are performing lab tests on the materials that are being used in the Vergaderfabriek (this process runs parallel to the project). Their scientific evidence will be used to demonstrate safety, which is required for the building permit in the DO phase.

Revelating (REV)
Consulting on implementing (among others) 3D printing in organizations, from strategy development to delivery. Role in this project was advising during the early stages in the project (initiative/hackathon, procurement), and facilitating communication between the parallel processes of the municipality Voorst, TU Eindhoven and the project process. A final role is to ensure that the VO is aligned with the program of requirements defined by the client.

Lexence Advocaten (LA)
Law firm. Bas Martens provided legal support in creating the contract for the consortium of the Vergaderfabriek.

De Slaapfabriek (SLA)
A hotel and meeting location in Gelderland. In collaboration with C4M they initiated the project. De Slaapfabriek is the client of this project.

Centre4Moods (C4M)
Realizes new methods of experiencing in meetings by sound en sensing technology. In this project they have the role of providing the sensing and sound technologies that improve the experience of the meetings held in the building.

Gemeente Voorst (GV)
Municipality in Gelderland. They play a key role as they have the power to grant a building permit for the building to be constructed in a later phase. Involving and educating them early on increases the chances that they will approve the permit.

6. Do you know if there were any contracts installed between the involved actors? If so, between which actors?

Bas Martens (Lexence Advocaten) has helped to set up a unique collaboration contract between the parties involved. In this contract, parties can realize their own goals and manage their risk and uncertainties, because they are not bound to particular outcomes. The contract could be framed as a "statement of intent" between all parties, which is very different from the traditional method of procurement.

Project activities

Activity Themes	**Applicable? (check box if applicable)**
Client themes	
Client actions	X
Contracts	X
Program of requirements	X
Other:	

Design themes	
Architectural Design	X
Interior	X
Landscape	X
Building physics & Acoustics	X
Structural/Civil	X
Installations	X
Geotechnical	X (Traditional)
Design integration	X
Other:	
Project Management Themes	
Organization/process integration	X
Information/communication	X
Risk management	
Other:	X (assessing knowledge in participants during tender, what do they know, what don't they know). Align

7. Can similar themes be identified for the project phases you mentioned? If not, what themes existed in the project?

See table above.

8. Which themes required the most attention?

Design integration. Input is provided by all disciplines which is specific for their discipline and independent from the input of other actors. Balancing the input from these disciplines, as well as integrating 3D printed elements with traditional methods of construction requires significant effort.

9. Was communication ad-hoc or planned?

Regular meetings between organizations were organized and communication was facilitated in the parallel processes.

10. Was there a project manager installed to coordinate the process? If not, who coordinated the process in the project?

Revelating had a role in facilitating the process from inception until the project's current state.

3. Specific questions per lifecycle phase

This part contains specific questions on each previously listed lifecycle phase in the project

11. What was the goal and the key activities of each stage that was previously mentioned?

1 Initiative

2 Project definition (goal: creating program of requirements)

3 Hackathon (goal: creating a conceptual design)

4 Procurement (goal: forming the consortium to realize the design)

- Approaching potential partners for consortium

- Assessing competencies organizations (what do you know, what don't you know, cross referencing with other organizations).
- Writing a contract between the organizations in the consortium

5. Printing Strategy/VO (goal: develop a workable conceptual design that meets the program of requirements)

- Framing the uncertainties in the project. Specify project-independent and project-specific questions. The project independent questions can be forwarded to the TU/E, the project specific questions should be solved by the design team.
- Parallel processes. One with the municipality (involvement and educate them for permit), one with the project (creating VO), and one at the TU/E (material development and lab tests for verification of structural integrity in later stage)
- Diverging (generating alternatives). Whiteboard is most important tool in this phase, sketches are made with input from all disciplines which is then discussed with the rest of the team. Conceptual integrated solutions are created that could meet requirements from disciplines.
- Converging. Choosing alternatives for more detailed development. If this detailing presents new challenges or potentially better alternatives the process goes to the diverging phase again. *This diverging and converging process has been gone through three iterations in this project*
- Creation of a parametric model that is currently undergoing structural calculations.
- Facilitating communication between the parallel processes
- Educating permit provider (and other actors) on the technology
- Verifying VO is aligned with the program of requirements.

Note: in a later DO stage, there are less more detailed alternatives, but the amount of players (suppliers) increases. All have more specialized knowledge on their domain, which should be integrated in the design (as well as the testing results from TU/E). In theory it is possible that the design turns out to not meet the requirements and will have to go back to the VO phase, although this is not expected in this project.

12. Which actors were responsible for and contributing to these activities? (RASCI)[13]

The table below was filled in to own interpretation based on Jager's answers. In reality there could be minor deviations in the responsibilities of the actors.

Key Activity	**W&B**	**CyBe**	**REV**	**SLA**	**VW**	**TFF**	**LA**	**EN**	**C4M**	**GV**	**TU/E**
1. Initiative			S	A							
2. Project Definition			S	A							
3. Hackathon		S	S	A		R					
4. Procurement											
Approaching potential partners for the consortium		S	R	A		S					
Assessing competencies organizations		S	R	A		S					C
Writing a contract			S	A			R				
5. Developing VO/Printing Strategy (iterations)											
Framing uncertainties	C	C	R	I	C	C		C		C	C
Diverging (generating alternatives)	S	S	C	I	S	A		S		C	

[13] RASCI is a method to clarify the responsibilities for activities within a project. R = Responsible (verantwoordelijk), A = Accountable (aansprakelijk), S = Supporting (Steunen), C = Consulted (raadplegen), I = informed (informeren).

Converging (selecting alternatives)	S	C	C	C	C	A		C			
Creating a parametric model for structural calculations	R					A					
Facilitating communication between parallel processes (TU/E, Project, Municipality)			R								
Educating permit provider (and other actors) on the technology			R								
Lab testing Material		I	I			I					R
Verifying whether VO is aligned with program of requirements			R	A							

4. Challenges

13. Can you give examples of organizational challenges that were encountered during the project? How did you deal with these?

-

14. How did you verify the strength/stiffness and stability of the structure?

TU Eindhoven is doing research on materials used for the construction of the Vergaderfabriek. During the DO phase, these findings will be integrated in the design process to demonstrate that it is safe and can apply for a building permit. Another role of this scientific research is to validate the assumptions (based on experience) in the VO phase by the disciplines related to 3D printing.

15. What was the method of financing for the project (gift, co-financing, public funding, private investment)

Confidential

5. Concluding questions

16. How do you think the process could have improved?

Several obstacles were encountered along the way due to things that were not known upfront. If Jager would have to do the process again, he would not necessarily have done something different. The primary difference is that the knowledge would have increased and that the process could have gone a lot faster. A deadline was hard to predict in this project, because there were a lot of uncertainties from the start (new technology). From the moment the building permit is approved, it is easier to give a clear indication of a deadline, as it then begins to look more like a standard project.

6. Other

Recommendations for collaboration process

- In both organizations and projects a client with a clear vision, requirements and frames is key to realize a project
- Initially diverging to obtain the input from all disciplines. This is both an opportunity and a challenge since 3D printing allows for customization to increase performance of individual disciplines (acoustic for example), but the input from a discipline is independent from the input

of the other disciplines. Integrating these different perspectives and converging to a few alternatives is therefore a challenge.
- Creating a level playing field in terms of knowledge is something that can be a challenge when actors are culturally accustomed to the conventional way of working (installations follows the architect for example). Revelating plays a key role in educating actors how to think outside of the traditional framework. They educate both the actors themselves as well as how these actors can educate others. This is relevant for projects, because after the initial design (VO) players with more knowledge will be introduced in the process which again have to be educated on how to use the new possibilities (like form freedom).

Comments on (initially created from results of 3D-Printing in the Circular City" Project's) model

- In general a design can be verified in three stages: design, final product, and during the manufacturing. Something currently under development is that the verification procedures can take place during the manufacturing. Checking during manufacturing would be good because if you see that for example a tolerance is off you can stop the printing and not waste valuable materials. Another advantage over only testing the final product is that you can verify different types of elements with the same tests.
- The final phase is no different than the first cycle in system development. You do the cycle several times and the last cycle is the design. The same activities should be used because if you use a different finishing and cleaning this means you cannot use the verification methods used in the previous design cycles. Tests are performed under certain conditions and changing these conditions in the last cycle might make these tests invalid.
- The process is much more complex than your model shows. Adding diverging and converging (smallers circles and iterations) aspects would be wise.
- The degree of knowledge adoption determines the organizational structure. An analogy can be drawn from maturity models, literature states that the lowest maturity level of a department is the one governing the maturity level of the organization.
- Governing for the process are the Technology Readiness Levels. The lower they are, the more unknowns and uncertainties in the outcomes. At this point it becomes difficult to define all activities and outcomes upfront. This is an example where there are a lot of unknowns, some of which are general (project-independent), some of which are project specific. This makes it challenging to come up with a hard deadline. The best thing you can do is set up a process that allows the individual parties to realize their goals and limit their risks.

Remaining comments

- Elaboration on Innovation model:
    - Innovators (enthusiastic in the technology)
    - Early Adopters (Connecting the technology with applications in the industry)
    - Early Maturity ("Pragmatisten", only interested in applications). Have other priorities, worried about additional risk of applying 3DP (Little realized examples, performance over 30 years not guaranteed, less strength of material)

  In the innovation curve, only the first two groups (innovators and early adopters) are interested in the technology, the early majority and others are only interested in applications. This is both for 3DP and for other technologies. 3DP could be classified in between the early adopters and early maturity. By some this is referred to as a trench, because it is very difficult for a technology to go from the EA to EM.
- To know that you have to invest in a technology, you first need knowledge about a technology. BIM is also developing slowly largely because engineers do not yet know how to use it.
- Printing in concrete is primarily a material development challenge (which has seen development over the last few years). On the Vergaderfabriek project, robotic capabilities presents the boundaries, within which material development is the issue.

- It is likely that spaces are left open for installations. A part of the work will use traditional manufacturing methods (like foundations). The questions that arise during the VO and printing strategy phase have a "design integration" nature (combining conventional and 3D printing). For example, glass itself will not be printed, but has to be integrated in the structure.

Appendix E Interview R&Drone Laboratory (Berry Hendriks)

This appendix presents the results of the interview conducted with Berry Hendriks on the R&Drone Laboratory in Dubai.

1. General questions

This part contains general questions on lifecycle phases, involved actors, and identified activity themes per phase.

Life cycle phases
In a traditional Dutch project, several phases can be identified. For the manufacturing of a 3DP element, the phases below can be identified (model from Aerospace Industry). Please state if the phases are applicable to your project, and if not, which phases could be identified.

Lifecycle Phases Construction Project	Applicable? (check box if applicable)
Initiative/Feasibility	X
Project Definition	X
Design (VO, DO, TO)	X
Tendering	X
Execution Design (UO)	X
Construction	X
Usage/exploitation	
Other:	

Currently the R&Drone Laboratory project is in the final stages of construction. The 3D printed walls and roof are delivered by CyBe. The main contractor is now finalizing the works.

Phases 3D printed Element	Applicable? (check box if applicable)
System Development (Iterative process of phases below)	
Computer Aided Design (CAD)	X
Preparing the CAD for Printing	X
Machine Setup	X
Manufacture	X
Cleaning and Finishing	X (Curing done during process)
Verifying strength	X (Verification of material by compressive and tensile laboratory tests)
Transport	X (not the elements, but the printer)
Assembly	X (on site)
Other:	X

Though the phases mentioned in the interview show an overlap with the phases in the model above, CyBe uses a specific process for both technology development and construction. This is a system engineering model with several phases. First is the orientation, then design and engineering, then transport and preparation, then printing (and testing according whether it aligns with design and engineering), then finalizing construction.

1. In which of these phases were you involved?

All phases after the D&B contract was awarded.

2. In which phase was decided that 3DP would be used?

First phase. Dubai authority has announced to print 25% of their building in 2030. A requirement for this project was a 3D printed building, which was specified in the tender documents. and the D&B contract for this was awarded to CONVRGNT.

3. What was the motivation for using 3D printing?

A requirement for this project (as specified in the D&B contract awarded to the contractor) was that it should be 3D printed. However, using the technology offered several advantages in comparison to the traditional approach.

Reduced transportation Cost, since the elements were printed on site.

High speed construction process (3 weeks to standard 3 months). It should be noted here that there is a difference between netto printing speed and bruto printing speed. The 2,5 m tall elements can be printed in 50 minutes, allowing for about 14 segments a day. (or 28 elements in a day if it prints nonstop). However, the interfacing with conventional elements (CyBe had to wait for the works of main contractor for example) and setting up the printer takes additional time.

Sustainable (less waste, CO_2 emissions, reduced energy for transport, assembly, logistics)

Actors

In a traditional project, several standard actors can be identified. 3D Printing could introduce new actors in the process. Examples are mentioned below.

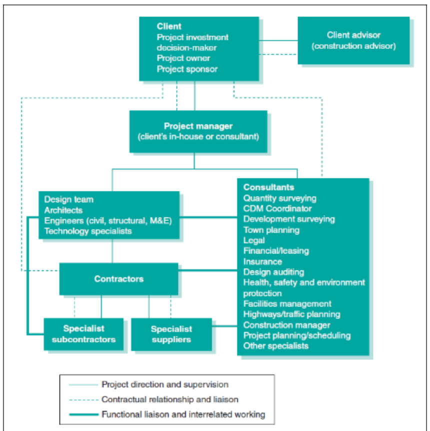
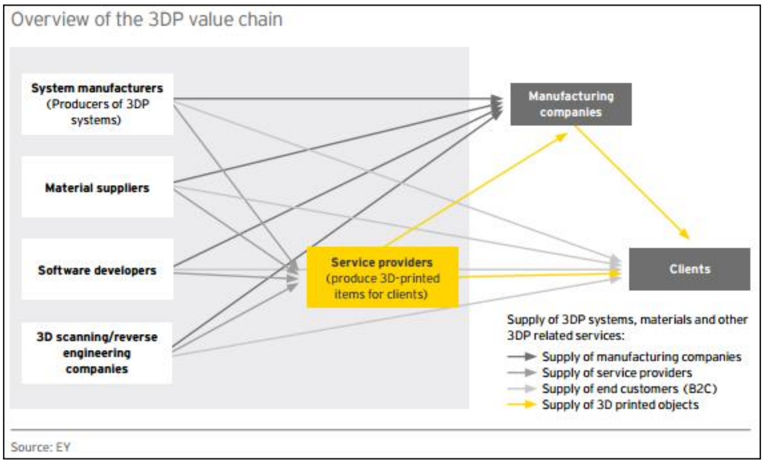


Figure 3.2 Typical project team structure.



4. Which one of these actors was present in your Project?

Actors	**Applicable? (check box if applicable)**
Client	X (DEWA)
Architect	X (Wanders Wagner)
Engineer	X (W&B)
Contractor	X (CONVRGNT)
Subcontractor	
Specialist consultants (i.e. Project Manager)	
Other:	X(Dubai Municipality, Dubai Central Laboratory)
Potential new actors	

Service Providers (delivers finished printed objects)	X(CyBe, 3DVinci)
3DP System supplier	
Software supplier	
Material supplier	
Other:	

5. What were the roles of the involved actors?

DEWA (Dubai Electricity and Water Authority)
(public) Client in this project. Dubai has announced that it is their goal to print 25% of their buildings in 2030. Following this statement, the public authority set as a prerequisite that the building must be printed.

CONVRGNT (CON)
Large Dubai-based contractor. They are the main contractor in this project and have a D&B contract with DEWA. They contracted out the 3D printing works to 3DVinci.

3DVinci
3DP service provider. Experience in printing (small) product scale elements with Materialise and Ultimaker. They did not have previous experience in construction process management which caused problems later in the project. They contracted out the conceptual design to Wander & Wagner and the Engineering and construction works to CyBe.

Wanders & Wagner (WW)
Responsible for architectural works. Provided the conceptual design of the printed works to 3DVinci on basis of which CyBe took over the engineering and printing of the elements.

CyBe
Responsible for engineering and construction of the 3D Printed outer walls and roof of the project. They contracted out the structural engineering of their elements to Witteveen & Bos.

Witteveen & Bos (W&B)
Engineering firm, was the structural engineer for the 3D printed walls and floors. The structural principles they created were incorporated in the parametric model created by CyBe (will be elaborated later)

Dubai Municipality
Public Organization. Provided the building permit required for the construction of the project.

Dubai Central Laboratory
Laboratory which is directly under the Dubai Municipality. Responsible for verifying the material used by CyBe, which form the basis for the building permit that was granted.

Rice Perry Ellis
Dubai based engineering firm. Was the lead engineer for the overall project.

6. Do you know if there were any contracts installed between the involved actors? If so, between which actors?

Yes, there were several contracts between organizations involved, in which the specific responsibilities and conditions were identified. CONVRGNT was the main contractor who outsourced a part of the work to 3DVinci and RPE, who then contracted out works to CyBe and WW. CyBe enclosed in the contract conditions of what 3DVinci should provide (like a structural engineer), which was likely not noticed by 3Dvinci. This led to the fact that later Witteveen & Bos was hired to do the structural calculations of the 3D printed elements (remunerated by 3DVinci).

The organizational structure was set up in a very hierarchical way, in which actors only talked to their immediate hierarchical links. Later in the project it turned out that this was the wrong approach because of bad interfacing between the planning for the printed works and the overall planning (there was initially no communication on the overall planning by the main contractor). The organizational structure is set out below:

Project activities

Activity Themes	**Applicable? (check box if applicable)**
Client themes	
Client actions	
Contracts	
Program of requirements	
Other:	
Design themes	
Architectural Design	
Interior	
Landscape	
Building physics & Acoustics	
Structural/Civil	
Installations	
Geotechnical	
Design integration	
Other:	
Project Management Themes	
Organization/process integration	
Information/communication	
Risk management	
Other:	

7. Can similar themes be identified for the project phases you mentioned? If not, what themes existed in the project?

Themes for the overall project are unclear, because CyBe scope of work only executed the 3D printed works. They had interfaces with conventionally fabricated elements, the architectural design, structural calculations and installations which had to be integrated in the elements.

8. Which themes required the most attention?

The design integration took substantial effort in a later part of the project because the topic did not receive sufficient attention during the early stages of the project.

9. Was communication ad-hoc or planned?

Communication was only done to the direct links in the hierarchy. This meant that initially there was no communication between CONVRGNT and CyBe. This caused problems later in the project when the planning turned out to be very different.

10. Was there a project manager installed to coordinate the process? If not, who coordinated the process in the project?

CONVRGNT was the main contractor.

2. Specific questions per lifecycle phase

This part contains specific questions on each previously listed lifecycle phase in the project

AM project phases

11. What was the goal and the key activities of each stage that was previously mentioned?

This process is based on the perspective of CyBe (not the main contractor for which the exact phases are not known)

1 Orientation Selecting Partners

- Setting up contracts specifying responsibilities, conditions and requirements.

2 Design + Engineering

- Creating conceptual (sketch) design
- Creating a parametric model with structural principles (input contourlines and requirements like offset, width, column dimensions for sufficient reinforcement). This took 6 weeks now, but only has to be done once. In the next project it can be done in 2 days.
- Performing structural calculations on the digital design to verify strength.
- Labtests to verify strength of material used
- Building Permit request
- Creating 3DP protocols ("Werkplannen")

3 Transport and preparation

- Transporting Printer to site
- Site preparation (material, generator). A tent was put around the construction site to protect the (temporary wet) building elements from external influences like sand storms.

4 Printing

- Interfacing with conventionally manufactured elements on site (like piping and electricity). Some conflicts had to be resolved during construction. Agreeing on reference points was helpful here.
- Printing of bottom segments directly on their location. Reinforcement was put in a number of contours and concrete was cast in. This enabled a bending stiff connection between roof and walls, providing structural integrity. Small tubes and sockets can be manually inserted during the printing process. 2 men were present during the construction process and responsible for this. The elements are vertically joined. Isolation was later put on the inside of the walls by the main contractor. Curing (spraying with water) should be done in sufficiently harded lower layers while the element is being printed to prevent cracking in a later stage.
- Printing the smaller top segments ("Borstwering"). These elements were made on-site but had to be hoisted and assembled to their right location.

5 Finalizing construction

- currently in this phase.

12. Which actors were responsible for and contributing to these activities? (RASCI)[14]

Key Activity	**CON**	**3DV**	**CyBe**	**WW**	**W&B**	**DM**	**DCL**
1 Orientation							
Selecting Partners	R		S				
Contracts and conditions (between all partners)	R	R	R	R	R		
2 Design and Engineering							
Creating conceptual Design				R			
Parametric Model incl structural principles			R	S			
Structural calculations on model			I		R		
Verification materials							R
Providing building permit						R	
Printing Protocols			R				
3 Transport and preparation							
Site Preparation (creating conditions for 3DP)	R		S				
Printer Transport			R				
4 Printing							
Interface/conflict resolution 3DP elements with traditional construction	R		S				
Printing bottom segments			R				
Printing Top segments			R				

3. Challenges

13. Can you give examples of organizational challenges that were encountered during the project? How did you deal with these?

CONVRGNT initial approach was to manage the project in a traditional way. This can be seen as a failure factor since the 3DP elements required tuning/coordination ("Afstemming") with the traditional parts of the building. This lack of communication was reinforced by the hierarchical setup of the project organization. People only talked to their direct links in the organizational structure, meaning CyBe had no direct communication with CONVRGNT. There were also cultural differences. CyBe has a more western culture, in which emphasis and creativity is put on the design and engineering work. Creative thinking during construction is the limited. In middle eastern culture however, the emphasis and creative thinking is often done during the construction process. These factors resulted in a discrepancy in the planning between CyBe (relatively long design and engineering) and CONVRGNT (faster construction), leading to conflicts later in the process.

3DVinci had no previous experience with construction. This caused process coordination problems and in January 2017 the project organization reformed, allowing contact between CyBe and CONVRGNT. During this re-organization there was conflict between several organizations and legal proceedings

[14] RASCI is a method to clarify the responsibilities for activities within a project. R = Responsible (verantwoordelijk), A = Accountable (aansprakelijk), S = Supporting (Steunen), C = Consulted (raadplegen), I = informed (informeren).

followed. The responsibility for performing the structural calculations on the 3D printed elements was not clear across the organization. RPE did not have experience with it and 3DVinci did not know how to do it. CyBe specified that this was not in their scope and later hired Witteveen & Bos to perform these calculations.

14. How did you verify the strength/stiffness and stability of the structure?

Design by testing standard (EN1990) from the Eurocode was used. This is about testing a representative element with a representative load. Tensile and compressive strength of the printed material was tested in a laboratory and structural calculations with these characteristics were done by Witteveen & Bos. These were sufficient to obtain the building permit, although it should be noted that requirements and conditions for the granting of a building permit are less extensive in Dubai than in the Netherlands.

Important to note is that CyBe is not responsible for demonstrating structural safety. This is the responsibility of the main contractor.

15. What was the method of financing for the project (gift, co-financing, public funding, private investment)

Client financed (DEWA).

4. Concluding questions

16. How do you think the process could have improved?

The employed process worked well for CyBe during this project, and if the same parametric tool can be used in a next project it will go a lot faster. Hendriks sees the following future developments and opportunities for his technology.

First is a different design process in which a computer generates the alternatives instead of a human. This allows for more iterations and feedback loops in the design and results in a faster overall process.

Secondly, there is an opportunity for developing a business case ("seriebouw"). Going from project to project and developing the (Rhino) script every time is far less efficient than when a similar script can be used for a whole area (like a VINEX area). There could still be customization in such an area for individual needs, (the created model includes as input the orientation to the street and sun, surface area's for living rooms, structural principles by W&B, and external contour lines at three heights) because the program automatically generates the floor plan. Based on this start, you only have to do the last 20% yourself of design. By developing a full business case you take advantage of the generative abilities of the Rhino model.

Based on experience in another project, Hendriks thinks the intervention of authoritative figures in the content of the process planning is not beneficial for the project.

Remaining comments

- The requirements for isolation in Dubai are less strict. "Koudebruggen" are therefore less important. The fact that these will likely be present in the floor is therefore not an issue.
- Responsibilities for defects were allocated in such a way that if a defect is the direct result of the printer, it is CyBe's responsibility. However, if the defect can be traced back to interference with a traditional element the main contractor is responsible.
- Values for tensile and compressive strengths were calculated by the Dubai Central Laboratory and were used as input for the structural calculations. Because of the large amount of safety factors there was a large difference between the average value and the design value for the printed works.

- There are three ways of printing. Directly on site, an on site factory and offsite. In this project the first two categories were used.
- The bottleneck for netto printing speed is primarily in the interfacing with the main contractor.

Appendix F Interviews MX3D Bridge (Bertrand Le and Tim Geurtjens)

This appendix provides the results of the interviews that were conducted for the MX3D bridge. Two interviews were conducted, with Bertrand Le from Arup (first chapter) and Tim Geurtjens from MX3D (second chapter)

1 Interview Bertrand Le

1. Introduction

The case under study is a printed metal bridge project initiated by MX3D. The interviewee is Bertrand Le. He is an associate from Arup, who was leading the Arup design team that was developing a preliminary structural design for the bridge.

It is important to note that not all questions could be answered in full, because Arup works as an engineering consultant and does not have the complete overview of the project. For questions where there was some uncertainty in the answers, cross-referencing was applied through an interview with MX3D's CTO and cofounder: Tim Geurtjens (see chapter 2).

2. General questions

This part contains general questions on lifecycle phases, involved actors, and identified activity themes per phase.

Life cycle phases
In a traditional Dutch project, several phases can be identified. For the manufacturing of a 3DP element, the phases below can be identified (model from Aerospace Industry). Please state if the phases are applicable to your project, and if not, which phases could be identified.

Lifecycle Phases Construction Project	Applicable? (check box if applicable)
Initiative/Feasibility	**X**
Project Definition	**X**
Design (VO, DO, TO)	**X (VO)**
Tendering	
Execution Design (UO)	
Construction	**X**
Usage/exploitation	
Other:	

Tendering not relevant because client is doing the coordination and manufacturing in-house. Though normally the design has multiple stages, the decision was made to move from VO to construction (see chapter 2 for more elaboration)

Phases 3D printed Element	Applicable? (check box if applicable)
System Development (Iterative process of phases below)	
Computer Aided Design (CAD)	
Preparing the CAD for Printing	
Machine Setup	
Manufacture	
Cleaning and Finishing	

Verifying strength	
Transport	
Assembly	
Other:	

Arup was not involved in the themes above, therefore it is not clear exactly which activities are performed.

1. In which of these phases were you involved?

Project definition to create program of requirements, and VO.

2. In which phase was decided that 3DP would be used?

In the initial phases of the project.

3. What was the motivation for using 3D printing?

MX3D is a startup which is developing their AM steel technology. The bridge was chosen as something to apply and showcase MX3D's metal printing technology to. They want to show that 3D printing brings something new to the world. This means that 3D printing was not necessarily selected for the project, but the project was selected for 3D printing.

4. Which one of these actors was present in your Project?

Actors	**Applicable? (check box if applicable)**
Client	X (MX3D, potentially municipality)
Architect	X (Joris Laarman, MX3D)
Engineer	X (Arup)
Contractor	X (Heijmans, played role of initial designer though, not a contractor in this project)
Subcontractor	
Specialist consultants (i.e. Project Manager)	
Other:	
Potential new actors	
Service Providers (delivers finished printed objects)	X (MX3D)
3DP System supplier	X (ABB)
Software supplier	X (Autodesk, Delcam)
Material supplier	X (Arcelor Mittal)
Other:	X (Sponsors & Partners)

5. What were the roles of the involved actors?

This question is further elaborated in chapter 2.

6. Do you know if there were any contracts installed between the involved actors? If so, between which actors?

Confidential

7. Please state which of these activity themes were applicable to your project. If they were not applicable, please state which themes were applicable in your project.

Activity Themes	**Applicable? (check box if applicable)**
Client themes	

Client actions	X
Contracts	X
Program of requirements	X (for the work done by Arup)
Other:	
Design themes	
Architectural Design	X (MX3D)
Interior	
Landscape	
Building physics & Acoustics	
Structural/Civil	X
Installations	
Geotechnical	X (capacity of retaining wall as design constraint, but not an active element in design process)
Design integration	X
Other:	
Project Management Themes	
Organization/process integration	X (MX3D)
Information/communication	X (MX3D)
Risk management	X (risk assessment MX3D with municipality)
Other:	

Comment: There were not so many disciplines, only the architectural expectations, client demands and structural engineering work. There was no direct communication between Arcelor Mittal, ABB robotics, Universities and Arup. Communications went through MX3D.

8. Can similar themes be identified for the project phases you mentioned? If not, what themes existed in the project?

Some are applicable, as indicated in the table.

9. Which themes required the most attention?

Not in Arup's position to answer.

10. Was communication ad-hoc or planned?

Ad-Hoc. (as soon as problems occur they are solved/learning by doing)

11. Was there a project manager installed to coordinate the process? If not, who coordinated the process in the project?

MX3D has a managing team of 3 people, which are overseeing and coordinating their on-going projects.

3. Specific questions per lifecycle phase

This part contains specific questions on each previously listed lifecycle phase in the project

AM project phases

12. What was the goal and the key activities of each stage that was previously mentioned?

1 Initiative/feasibility

- Selecting partners and securing financing (for the whole company)
- Forming project team
- Selecting a location
- Creating conceptual design

2 Project definition

- Developing a shared starting point/assumptions and goal for the project
- Creating a program of requirements (for design and structural design) work
- Setting up a contract

3 VO

- Weekly progress Meetings
- Changing initial design to reduce uncertainty (Arup helped reduce the complexity and uncertainties of the initial design to make the bridge more feasible)
- Selecting optimal type of stainless steel to use in the bridge
- Providing test-results of materials
- Defining relevant characteristics and and parameters for structural calculations
- Preliminary design (shapes, geometry joints, section properties, global time estimation, main calculations, steel quantities required)
- Providing recommendations for further testing on defining parameters required in DO
- General recommendations for DO

Was the software you used applicable for the material properties manufactured by AM? (heterogeneous, discontinuous, unknown exact properties)

During our work on the project, yes. In the VO stage you simplify the geometry and make general calculations, for which existing software is valid. During DO you will go more into detail on the specific sections. In some software programs programming heterogeneous materials and properties is already possible. However, further testing is required to specify the exact material properties in this project.

Did you seek partnership with Universities or Arcelor Mittal regarding material properties?

No, but Le understands the role universities can play in these type of problems. The further a structure is away from the conventional production, the less applicable the codes are. The municipality has some expertise regarding the evaluation, but if it gets too complex they turn to institutes (who help writing the codes). Their input can then indeed be used to demonstrate safety.

Universities often approach problems in a very theoretical way (the what) though, with limited focus on practical application and feasibility within a certain budget and schedule (the how, when and who) Arup is a company that can bridge this gap.

13. Which actors were responsible for and contributing to these activities? (RASCI)[15]

Key Activity	MX3D	Arup	MUN	HM	ABB	AM	Sponsors
1 Initiative/feasibility							
Selecting partners/securing financing	A						I
Forming Project Team	A						
Selecting a location	A		S				
Creating conceptual design	A			S			

[15] RASCI is a method to clarify the responsibilities for activities within a project. R = Responsible (verantwoordelijk), A = Accountable (aansprakelijk), S = Supporting (Steunen), C = Consulted (raadplegen), I = informed (informeren).

2 Project Definition							
Developing a shared starting point/assumptions and goal for the project	A	S					
Creating a program of requirements (for design and structural design) work	A	S					
Setting up a contract	A	S					
3 VO	A	R					
Weekly progress meetings	A	R					
Changing initial design to reduce uncertainty	A	R					
Selecting optimal type of stainless steel for AM		R					
Providing test-results of materials	A	I					
Defining relevant characteristics and and parameters for structural calculations	A	R					
Preliminary design (shapes, geometry joints, section properties, global time estimation, main calculations, steel quantities required)	A	R					
Providing recommendations for further testing on defining parameters required in DO	I	R					
General recommendations for DO	I	R					

4. Challenges

14. Can you give examples of organizational challenges that were encountered during the project? How did you deal with these?

The starting point and perspective for this project was different for MX3D and Arup. MX3D approached the project as a product, which would also function as a bridge. Arup viewed it as a bridge with good aesthetics. The latter introduces a significant amount of additional requirements (open to public, demonstration of safety, building permits). These two perspectives took some time to converge to a shared prevailing perspective. Overall though, MX3D were great partners to work with.

15. How did you verify the strength/stiffness and stability of the structure?

Verification done during the design stage was done through a simplified, structural 3D model. Assumptions were made on parameters, based on the material tests that were presented by MX3D. Elements like strength, stability and stiffness were considered.

Additional verification would be required during DO, manufacture and perhaps when the bridge is completed.

16. What was the method of financing for the project (gift, co-financing, public funding, private investment)

Investments from partners, in-kind contributions. Municipality as potential client for the bridge.

5. Concluding questions

17. How do you think the process could have improved?

Involving the municipality more often would be helpful to increase chances of realizing a bridge that is demonstrated to be safe and open to the public. (since the municipality can provide the building permit).

The different perspectives (bridge or artefact) on the project took some time to converge.

There was not a stable, committed project team continuously working on realization of the project. Throughout the project the team working on it changed (actors left and joined). For the project it would have been best to specify the skills and expertise that was required upfront, and having a stable project team working on its completion.

2 Interview Tim Geurtjens

The purpose of the second interview is to provide clarity on uncertain issues on the roles and responsibilities of all involved actors in the process. Additionally, several questions regarding the future outlook were asked.

1. Project governance

1. Based on the interview with Le, I identified multiple actors, but your website shows a lot more. Could you highlight which of them contributed to the MX3D project and what their role in the project was?

MX3D
MX3D is a startup that is developing metal additive manufacturing technology and creates products with it. They have had experience with multiple earlier projects and are now working on a functional steel bridge. They are the central organization in the project and are responsible for the coordination of the project. They are also responsible for the design and manufacturing of the bridge.

Arup
Engineering firm. Created the VO with the conceptual design from MX3D as input. Also provided recommendation for next steps in DO and execution, to realize the final project as a bridge which is open to the public.

Heijmans
Heijmans is a contractor. In the early phases of the project they supported MX3D in the initial conceptual design.

Lenovo
Chinese computer hardware and consumer electronics manufacturer. They made a VR model of the completed bridge which can be used for communication purposes.

TU Delft
University that has done tests for the material used by MX3D.

Municipality of Amsterdam
Potential client for the bridge and also potential building permit granter.

Partners
There are a lot of partners (including from the organizations listed above) that contribute or have contributed to the technology development and overhead for the project required for the bridge to be printed. Examples include:

- ABB Robotics, who supplied the robots and provides technical support.
- Welding specialists providing expertise and equipment for welding.
- Autodesk, who contributes to software development required.

2. What were the considerations in deciding to move from VO towards construction?

Going through all traditional phases like DO, TO takes a lot of time, energy and money, meaning the bridge is less likely to be realized.

Furthermore, for a proper DO, you need to have detailed properties of the material (including the influence of the manufacturing process). This still constitutes a degree of uncertainty in the project and will require additional testing. Until the detailed material properties are known, a full DO would be of little use.

An advantage is that the bridge is constructed in MX3D's laboratory, meaning that a building permit is not required for construction to commence. The bridge will be designed and built in such a way that the team has confidence that it will be strong enough, after which safety is planned to be demonstrated through testing (like a proof loading). As soon as this is done, it can be placed in the built environment.

3. Findings so far show that additional uncertainty is a key difference between a traditional project and project in which 3D printing is applied. This could be related to the material, the software, and the verification strategy. What are certainties and uncertainties in the MX3D project and how does the team plan to deal with these?

When looking at project management, two approaches can be distilled: waterfall and agile. In waterfall, everything is known upfront and you can plan to a specific outcome. The process is divided in stages with milestones that work to this (known) end result. For most construction projects (like housing) this approach works well.

When the exact end-result is not known in advance however, a large emphasis on detailed planning is not useful, as it is likely to change along with the final result. Agile is a different type of philosophy more suitable to this type of project.

4. Can you think of any improvements in the applied governance in your project?

While doing the project, it was discovered that the process of the MX3D project is very different from a traditional construction project (you have more uncertainty). It was sometimes difficult to convince the actors used to the traditional way of working that this type of project required a different approach. *"The building industry should realize that things are likely to change and make sure to adapt fast."* Agile seems to be more applicable than the waterfall approach.

2. Future Outlook

5. At the moment the value to cost ratio of 3D printing seems to be lower than that of (optimized) traditional manufacturing methods. At what point do you see this ratio change?

On the cost side it is unlikely that 3D printing will compete with traditional manufacturing methods. However, it can provide additional value in the form of freeform construction.

Cost is likely to be driven down once more companies start using the technology, it is unlikely though that the technology will become cheaper than traditional manufacturing methods. Metal AM is also still relatively slow for larger elements, though this could be increased in the future.

It can provide additional value in terms of placing material where you need it, though software still needs to be developed further to fully utilize this. There are likely elements in buildings which could benefit from more freedom in form. If these add more value than they cost compared to conventional methods, it is likely that clients will start using them.

It is unlikely though that the next step is either 3D printing or not at all. The technologies will likely complement each other. For some elements it might be more beneficial to use 3D printing (for example when a complex geometry is required), for others the traditional manufacturing methods work fine (You don't need printing for straight lines).

6. What niche markets do you think will emerge in the next 5 years? (where the opportunities are best utilized?)

In the steel industry there will likely be business cases for (metal) 3D printing. A lot of people are looking for them currently, including MX3D.

Elements that are very small are unlikely to be suitable for printing. Also very heavy elements are not likely to be printed (Since the time to manufacture it would be too long). In between, there are business cases examples where it could be applied, like propellers for ships.

The niche market MX3D is currently operating in is art, with the bridge being an expansion towards architecture. When decorative elements have to be applied in building projects however, there are more strict requirements. For example, you need to use a certified material of which you know more detailed properties. This constitutes an additional threshold for 3D steel printing to be applied in the built environment.

7. Do you foresee a future where we can print full buildings and infrastructure?

We probably can do it, but it is unlikely that it will happen. The fact is that for a conventional high-rise building you don't need freeform elements everywhere. Since the technology is still more expensive, it is (and likely will be) more cost effective to make the rectilinear forms using conventional manufacturing methods.

8. What partnerships do you foresee in the future, and who do you think is in the lead in bringing this technology forward in the construction industry?

Geurtjens thinks freeform provides possibilities for architects, who will start integrating it in their design. The manufacturing and construction side is then likely to follow. It is unlikely that the contractors will move it forward, as they are traditionally more conservative.

9. It is often stated that digital transformation will have strong couplings in the future, increasing its potential (as well as challenges). Which technologies do you think could be coupled with 3D printing, and what would be the results?

Printing technology requires a lot of data processing and management, for which other technologies can be helpful.

Software that is currently often used for 3D printing is Rhino and grasshopper. Other technologies could offer opportunities, like IoT to collect data on the manufacturing process, and big data and AI to process it towards relevant information.

Lenovo is currently creating an VR application in which the realized bridge can be viewed and experienced before it is completed.

Additional comments

A consequence of using 3D printing is that designing becomes exponentially more complex. The software would need to be capable to handle this complexity, as the current software used in the construction industry is often not supportive for freeform shapes.

An recent visit to Dubai revealed that there is a larger push to implement 3D printing (likely related to the vision of printing 25% of buildings in 2030), incentivizing the construction industry to innovate.

It took 20 years to certify fiber reinforced concrete, meaning the material certification is likely to remain a challenge for some time.

Appendix G Interview Great Pagoda (Salome Galjaard)

This appendix presents the results of the interview conducted with Salome Galjaard on the Great Pagoda project.

1. General questions

This part contains general questions on lifecycle phases, involved actors, and identified activity themes per phase.

Life cycle phases
In a traditional Dutch project, several phases can be identified. For the manufacturing of a 3DP element, the phases below can be identified (model from Aerospace Industry). Please state if the phases are applicable to your project, and if not, which phases could be identified.

Lifecycle Phases Construction Project	Applicable? (check box if applicable)
Initiative/Feasibility	X
Project Definition	X
Design (VO, DO, TO)	X (3DS, Arup)
Tendering	X
Execution Design (UO)	X (3DS)
Construction	X (3DS)
Usage/exploitation	
Other:	

Phases 3D printed Element	Applicable? (check box if applicable)
System Development (Iterative process of phases below)	n.v.t.
Computer Aided Design (CAD)	X
Preparing the CAD for Printing	X
Machine Setup	X
Manufacture	X
Cleaning and Finishing	X
Verifying strength	? (unclear)
Transport	X (finished dragons to site)
Assembly	X (offsite)
Other:	

Since 3D Systems is a company that has a lot of experience in manufacturing, it is likely that they did not have to develop new technology for this project.

Elaboration: Arup was approached by the client to evaluate the possibility of using 3D printing for the dragons. They made an initial proposal, which the client used as input for further work. HRP decided on the material (nylon), and made decisions on the type of finishing that would be applied. At this point, Arup was approached again to provide consultancy services related to evaluating the current state of work and giving recommendations on further stages. They also made a proposal to make the (detailed) design for the dragons and their connection to the structure. 3D systems, the involved producer of the dragons, was also interested in doing the design work and ended up doing both the final design and production of the works.

1. In which of these phases were you involved?

Arup was involved in the initiative (making a proposition for using 3D printing for the dragons), Feasibility and early stages of conceptual design (VO).

2. In which phase was decided that 3DP would be used?

After the initial consultation by Arup the client decided to use 3D printing.

3. What was the motivation for using 3D printing?

Option was chosen because the dragons had a large degree of complexity and required different sizes on the different roofs. The original plan was to carve the dragons out of wood (manually), which would take a long time and constitute high labor cost. Also, the weight of these wood dragons was considered a risk for the old structure. 3D printing offered several benefits in this project:

- Automating the process (speed increased, lower labor cost)
- Weight reduction (lattice structure of nylon is a lot lighter than solid wood)
- Allows for customization at little additional cost (The dragons on the rooftops would become slightly smaller towards the top of the building)

Actors
In a traditional project, several standard actors can be identified. 3D Printing could introduce new actors in the process. Examples are mentioned below.

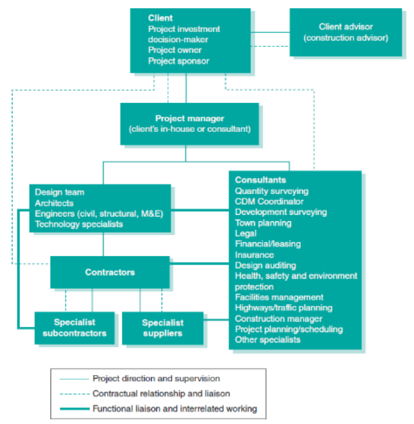
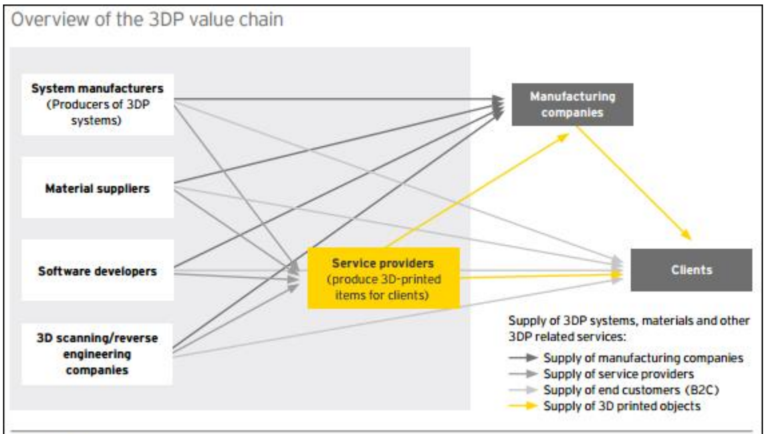


Figure 3.2 Typical project team structure.



Source: EY

4. Which one of these actors was present in your Project?

Actors	Applicable? (check box if applicable)
Client	**X (HRP)**
Architect	**X (Austin Smith Lord) – larger renovation project**
Engineer	**X (Hockley and Dawson) – larger renovation project**
Contractor	Not known for larger project.
Subcontractor	
Specialist consultants (i.e. Project Manager)	**X (Arup) – consultant for client on 3D printing, contracted under H&D**
Other:	

Potential new actors	
Service Providers (delivers finished printed objects)	**X (3D Systems)**
3DP System supplier	
Software supplier	
Material supplier	
Other:	

The dragons were an element of a larger renovation of the great pagoda, involving among others the client, architect and engineer. The main actors involved in the dragon elements were client, the engineer, Arup, and 3D systems.

5. What were the roles of the involved actors?

Historic Royal Palaces (HRP)
Client for the project, which had a coordinating role for the overall project and specified the assignment to Arup.

Austin Smith Lord (ASL)
Architect of the overall project, was not involved for the dragons.

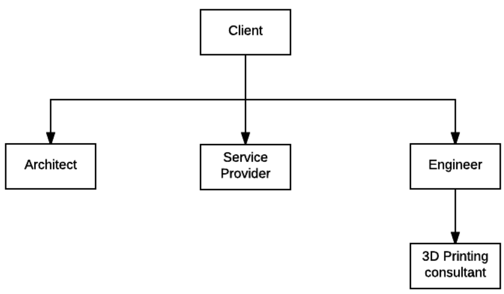
Hockley and Dawson (H&D)
Lead engineer for the overall project, had limited involvement in the design and production of the dragons.

Arup
Engineering firm. Consultant for the client during the initial phases of the project. Provided expertise on 3D printing feasibility and design.

3D systems
Service provider that produces finished products to clients. They ended up taking over the design work from Arup and produced the dragons for the project.

6. Do you know if there were any contracts installed between the involved actors? If so, between which actors?

A simplified organizational structure related to the dragons can be seen below. Arup had the role of 3D printing consultant for products in the built environment. Even though they were formally contracted under the engineer, they communicated directly with the client.



Project activities

Activity Themes	Applicable? (check box if applicable)

Client themes	
Client actions	
Contracts	
Program of requirements	
Other:	
Design themes	
Architectural Design	**X (dragons)**
Interior	
Landscape	
Building physics & Acoustics	
Structural/Civil	**X (safety dragon and design of bracket)**
Installations	
Geotechnical	
Design integration	**X (integrating with conventional building)**
Other:	
Project Management Themes	
Organization/process integration	**X**
Information/communication	
Risk management	
Other:	

7. Can similar themes be identified for the project phases you mentioned? If not, what themes existed in the project?

Not very applicable. The 80 dragons that have to be printed for this project could be classified as ornaments which should be integrated in the overall structure. This requires a limited amount of disciplines. Because the dragons had a large scale and would be positioned outside however, it had to be structurally verified and safety had to be ensured through adhering to standards and codes. Also, the ornaments needed assembly points to the overall structure, requiring engineering work to be done.

8. Which themes required the most attention?

Not applicable

9. Was communication ad-hoc or planned?

There were several client meetings on progress.

10. Was there a project manager installed to coordinate the process? If not, who coordinated the process in the project?

Client was responsible for process coordination. Not sure on exact activities in the overall project.

2. Specific questions per lifecycle phase

This part contains specific questions on each previously listed lifecycle phase in the project.

AM project phases

11. What was the goal and the key activities of each stage that was previously mentioned?

1 Inception/feasibility

- Evaluating traditional and 3D printing manufacturing methods
- Creating proposition document on 3D printing possibilities

2 Project Definition

- Making a virtual model of a dragon
- Selecting type of material and finishing
- Coating research
- Technical review (material, coating, regulations (verification), dragon design, bracket design)
- Initial structural calculations
- Recommendations for design stage

3 Design Dragons + Brackets

4 Manufacture & Finishing

5 Assembly, Transport

12. Which actors were responsible for and contributing to these activities? (RASCI)[16]

Key Activity	HRP	Arup	H&D	3DS
1 Inception/feasibility				
Evaluating traditional and 3D printing manufacturing methods	A			
Creating Proposition document on 3D printing possibilities	I	A		
2 Project Definition				
Making a virtual model of a dragon	R	I		
Selecting type material and finishing	R	I		
Coating research	A	I		
Technical review (material, coating, regulations (verification), dragon design, bracket design)	I	A		
Initial structural calculations	I	A		
Recommendations for design stage	I	A		
3 Design Dragons + Brackets	A		S	R
4 Manufacture & Finishing	A			R
5 Assembly, Transport	A		S	R

Arup made a proposal to also design the dragons and connections to the overall structure, but in the end these services were awarded to the producer (3D systems). It is possible that the client selected 3D systems over Arup because although they would likely deliver less quality in the design, they could do so at a much lower cost.

3. Challenges

13. Can you give examples of organizational challenges that were encountered during the project? How did you deal with these?

The process went very well. One thing that Arup did not have any experience with is having a producer involved during the design process that can potentially take over a part of their services in the project.

[16] RASCI is a method to clarify the responsibilities for activities within a project. R = Responsible (verantwoordelijk), A = Accountable (aansprakelijk), S = Supporting (Steunen), C = Consulted (raadplegen), I = informed (informeren).

The project was complex due to the many new elements, through good communication this did not become a problem.

14. How did you verify the strength/stiffness and stability of the structure?

The virtual model provided by the client was used for testing against regulations like wind and snow loads. During the technical review phase some initial calculations were made by Arup. It is not clear what the verification strategy 3D systems is currently applying.

15. What was the method of financing for the project (gift, co-financing, public funding, private investment)

The project was financed by the client.

4. Concluding questions

16. How do you think the process could have improved?

The process went very well, the relation with the client was very good. It would have been nice to continue working on the project during the design stage.

5. Remaining comments & Questions

- It was not originally expected that a producer would be a potential competitor in this project. The value of an engineering firm like Arup is that it delivers a high quality in its design. For example, Arup could have done optimizations on material thickness for the different dragons. The time spent on designing though costs time, driving up the price for the client. A producer that does not reach the same quality in design but can do it at a lower cost could then become an attractive alternative to clients.
- What made a decision like this easier to make for a client is that producer was already involved in the project. Also, 3D printing moves the design much closer to the production (there was no need for workplans or a different design for construction).
- Manufacturing constraints were less of an issue in this project because larger degrees of freedom can be achieved with printing in Nylon.

Do you foresee future competition for Arup from 3D systems or companies like Autodesk?

Introducing 3D printing in the value chain of projects could constitute a threat and offer an opportunity. A large contractor might buy a 3D printing service provider and do (or buy) the required engineering works in-house, meaning their services overlap with those of Arup. However, as long as these services are not intrinsically connected to other parts of the company, it is not likely it will be a competitor.

The same applies for Autodesk. Even if in the future they provide services that compete with Arup, they do not have the same passion for design and engineering work.

However, if producers start to deliver design services for free as an addition to their manufacturing services (like Philips for lighting), they become difficult to compete with as a design firm. This is somewhat similar to what happened in the Great Pagoda. If this happens more frequently in the future Arup will have to find an alternative position in the life-cycle process where it can add value.

An opportunity could arise when these players start to collaborate in projects more closely, where each actor does more work in his or her own specialism. This allows for better mutual understanding of the involved disciplines.

Appendix H Interview Post Aix en Provence

This appendix presents the results of the survey of the 3D printed concrete Post for a school in Aix en Provence, filled in by Nadja Gaudilliere.

1. General questions

This part contains general questions on lifecycle phases, involved actors, and identified activity themes per phase.

Life cycle phases

In a traditional Dutch project, several phases can be identified. For the manufacturing of a 3DP element, the phases below can be identified (model based on the Aerospace Industry). Please state if the phases are applicable to your project, and if not, which phases could be identified. Table 1 is applicable to the project of the school, table 2 is applicable to XtreeE's freeform concrete post.

Lifecycle Phases Construction Project	**Applicable? (check box if applicable)**
Initiative/Feasibility	**x**
Project Definition	**x**
Design (VO, DO, TO)	**x**
Tendering	**x**
Execution Design (UO)	**x**
Construction	**x**
Usage/exploitation	**x**
Other:	

Phases 3D printed Element	**Applicable? (check box if applicable)**
System Development	x
Computer Aided Design (CAD)	x
Preparing the CAD for Printing	x
Machine Setup	x
Manufacture	x
Cleaning and Finishing	x
Verifying structural integrity	x
Transport	x
Assembly	x
Other:	

1. In which of these phases were you involved?

XtreeE was involved in Execution Design and Construction.
XtreeE was involved in System Development, Computer Aided Design (in collaboration with other actors), in preparing the CAD for printing, in the Machine Setup, in the Manufacturing (in collaboration with other actors), in the cleaning and finishing and in the assembly (in collaboration with other actors).

2. In which phase was decided that 3DP would be used?

The idea appeared during the project definition (in France "Phase d'Avant-projet") and the decision was taken at the Execution Design phase (in France "Phase d'Exécution")

3. What was the motivation for using 3D printing?

The motivation for using 3D printing was, at the beginning, the architect's will. He had a specific shape in mind for the pillar and knowing XtreeE and our activities, he maintained the shape in the different stages of the project, as he was aware we could build it. Given the complexity of the shape envisioned for the pillar, resulting from a topological optimization, it was indeed ideal to 3D print it.

Actors
In a traditional project, several standard actors can be identified. 3D Printing could introduce new actors in the process. Examples for the actors in conventional projects and in the 3D printing industry are mentioned below.

4. Which one of these actors was present in your Project?

Actors	**Applicable? (check box if applicable)**
Client	**x (Métropole d'Aix-Marseille)**
Architect	**x (Marc Dalibard)**
Engineer	**x (Artelia)**
Contractor	**x (AD Concept)**
Subcontractor	
Specialist consultants (i.e. Project Manager)	**x (Fehr Architectural)**
Other:	
Potential new actors	
Service Providers (delivers finished printed objects)	**x (XtreeE)**
3DP System manufacturer	
Software supplier	
Material supplier	**x (LafargeHolcim)**
Other:	

5. What were the roles of the involved actors?

XtreeE had no contact with the client, Métropole d'Aix-Marseille. XtreeE handled the design of the geometry and the manufacturing files, based on the information given by the architect, Marc Dalibard, and in collaboration with the engineer, Artelia, and the concrete precast company, Fehr Architectural. LafargeHolcim supplied the concrete used by XtreeE to print the envelope of the post. Afterwards, the parts of the envelope were sent to Fehr Architectural for them to cast Ductal inside. Assembly and placement on site were then handled by AD Concept under the supervision of XtreeE.

6. Do you know if there were any contracts installed between the involved actors? If so, between which actors?

Contracts were already installed between the architect, Marc Dalibard, and the client, Métropole d'Aix-Marseille, for the project design. The contractor, AD Concept, was as well already chosen. Finally, a preexisting R&D contract between the material supplier, LafargeHolcim, and XtreeE, also existed.

7. Was there a project manager installed to coordinate the process? If not, who coordinated the process in the project?

The main project managers were the architect, Marc Dalibard for the global project and Philippe Morel, XtreeE's president, for the 3D printing of the post.

2. Specific questions per lifecycle phase

This part contains specific questions on each previously listed lifecycle phase in the project

AM project phases

8. What was the goal and the key activities of each stage that was previously mentioned?

Please list the phases and their key activities on a general level.

System development : 1) Identify the fabrication strategy; 2) Adapt XtreeE's printing system to the requirements set for the printing of the parts of the post.
Computer Aided Design : 1) Design the exact geometry of the post through a topological optimization; 2) Determine how to split the post and how to assemble it.
Preparing CAD for printing : 1) Code the manufacturing files for XtreeE's printing system.
Machine Set-Up : 1) Calibrate the printing system; 2) Test the printing path; 3) Prepare the concrete mixing system.
Manufacture : 1) Mix the concrete; 2) Print the envelope parts; 3) Cast the Ductal inside the envelope;
Cleaning and Finishing : 1) Sanding of the parts; 2) Coating of the envelope.
Verifying Structural Integrity : 1) Defining the load case for the topological optimization; 2) Validate the fabrication strategy; 3) Validate the manufacturing.
Transport : 1) Transportation to the Ductal casting site; 2) Transportation to the construction site.
Assembly : 1) Assembly of the parts of the post.

9. Which actors were responsible for and contributing to these activities? (RASCI)[17]

Please list which actors were responsible (doing the work), accountable (receiving the deliverable), supporting (contributing to deliverable), consulted (like expert opinions), and informed for the activities mentioned in question 8.

Key Activity	**XTreeE**	**Artelia**	**Fehr Architectural**	**AD Concept**
Identify the Fabrication Strategy	R	S	C	I
Adapt XtreeE's Printing System	R	I	I	I
Design of the Geometry through Topological Optimization	R	R	I	I
Determination of the Assembling Strategy	R	S	S	C
Code the Manufacturing Files	R	I	I	I
Calibrate the Printing System	R	I	I	I
Test the Printing Path	R	I	I	I
Prepare Concrete Mixing Area	R	I	I	I
Mix the Concrete	R	I	I	I
Print the Envelope Parts	R	I	I	I
Cast the Ductal Inside the Envelope	A	I	R	I
Sanding of the Parts	R	I	I	I
Coating of the Envelope	R	I	I	I
Define the Load Case	A	R	I	I
Validate the Fabrication Strategy	A	R	I	I
Validate the Manufacturing	A	R	S	I
Transportation to the Ductal Casting Site	A	I	A	I
Transportation to the Construction Site	A	A	I	A
Assembly of the Parts of the Post	A	C	I	R

[17] RASCI is a method to clarify the responsibilities for activities within a project. R = Responsible, A = Accountable, S = Supporting, C = Consulted, I = informed.

3. Challenges

10. Can you give examples of organizational challenges that were encountered during the project? How did you deal with these?

Given the innovative character of the Aix-en-Provence post project, several organizational challenges were encountered. First, the absence of construction regulations in France regarding 3D printed objects was a major issue. As there are no existing regulations and very slow existing processes to obtain safety insurance on innovative construction technologies, we had to find another way to guarantee safety and structural integrity on the post. We worked closely with the engineer to determine a manufacturing process that would enable us to fit into existing regulations, and allow us to have insurances on the post. A second example that can be given of organizational challenges met during the design and construction of this project is the complications brought by the decision we took to cast UHPC Ductal concrete inside the post. Construction companies need a specific license to be authorized to cast Ductal, so we had to find a precast company able to do it (Fehr Architectural). We also had to determine how to deal with transportation issues: the post was printed in Paris, but Fehr's casting infrastructures are in Germany and the construction site was in Aix-en-Provence. These various geographical positions implied a lot of transportation, and we had to find a way to ensure the success of the project while avoiding too much transport.

11. How did you verify the strength/stiffness and stability of the structure?

The verification of the structure was made with the help of the results XtreeE had obtained regarding the mechanical performances of 3D printed concrete through earlier tests on samples. Based on these results and on the fabrication method (Ductal cast in a 3D printed concrete envelope), Artelia's engineering team could verify the strength and stability of the structure.

12. What was the method of financing for the project (gift, co-financing, public funding, private investment)

    The financing method for the project was public funding (the client was the city of Aix-en-Provence).

4. Concluding questions

13. How do you think the process could have improved?

We identified several ways in which our fabrication process could have improved after working on that project. The main ones are linked to the organizational challenges we met. The establishement of construction regulation for 3D printed structures will greatly simplify the obtention of guarantees on structural integrity and safety. Also, having either on site 3D printing or larger production sites with several fabrication possibilities at the same place will help with manufacturing processes and transportation.

Appendix I Interview Landscape House (Chris Jonker)

This appendix presents the results of the interview conducted with Chris Jonker on the Landscape House project.

1. General questions

This part contains general questions on lifecycle phases, involved actors, and identified activity themes per phase.

Life cycle phases
In a traditional Dutch project, several phases can be identified. For the manufacturing of a 3DP element, the phases below can be identified (model from Aerospace Industry). Please state if the phases are applicable to your project, and if not, which phases could be identified.

Lifecycle Phases Construction Project	Applicable? (check box if applicable)
Initiative/Feasibility	X
Project Definition	X
Design (VO, DO, TO)	X
Tendering	
Execution Design (UO)	
Construction	
Usage/exploitation	
Other:	

Jan Jaap Ruissenaars developed a conceptual design of the landscape house for a design competition in Ireland in 2011. Though he did not win the competition, he looked for developers that could build his design. When BAM was approached, they stated the design could not yet be built, and that methods first had to be developed to achieve this. After some BAM decided they would contribute to the technological development required by participating in FabCity 2016, an initiative from the EU to explore new innovations and research. On location, a printer was installed after which a "learning by doing" R&D phase took place (described in the phases in the table below). The project is currently still in the VO phase, as BAM is looking for a client or investor to further finance the project. No detailed plan exists yet for DO and later construction.

Phases 3D printed Element	Applicable? (check box if applicable)
System Development (Iterative process of phases below)	X
Computer Aided Design (CAD)	X
Preparing the CAD for Printing	X
Machine Setup	X
Manufacture	X
Cleaning and Finishing	X
Verifying strength	X
Transport	
Assembly	
Other:	

The phases above have been gone through for small building blocks printed by the 3D Builder (the project's 3D printing system). A lot of work had already been done by Enrico Dini prior to project start.

1. In which of these phases were you involved?

In the system development phase which followed the conceptual design. The most active involvement was during the FabCity 2016.

2. In which phase was decided that 3DP would be used?

The architects design contained double curved concrete surfaces, which could not be manufactured with traditional methods. 3D printing was considered during the design (VO) of the building.

3. What was the motivation for using 3D printing?

The architects design contained double curved concrete surfaces, which could not be manufactured with traditional methods. 3D printing was considered as a technology that would enable making these. The motivation could therefore be classified as aesthetic.

Actors
In a traditional project, several standard actors can be identified. 3D Printing could introduce new actors in the process. Examples are mentioned below.

4. Which one of these actors was present in your Project?

Actors	**Applicable? (check box if applicable)**
Client	? (looking for one)
Architect	X (Universe Architecture)
Engineer	X (BAM)
Contractor	X (BAM)
Subcontractor	
Specialist consultants (i.e. Project Manager)	
Other:	
Potential new actors	
Service Providers (delivers finished printed objects)	X (Enrico Dini)
3DP System supplier	X Acotech (robots) , Enrico Dini (printing nozzle)
Software supplier	X (Enrico Dini, Acotech)
Material supplier	
Other:	X Hogeschool van Amsterdam

In practice there were more actors that contributed towards its development. The website http://landscapehouse.nl/info provides a list of all actors involved in the process. Jonker is not aware of the exact role of these actors, but they had a small or indirect role during the technical development, which is why they are not mentioned in this report.

5. What were the roles of the involved actors?

Jan Jaap Ruissenaars (Universe Architecture) (UA)
Jan Jaap Ruissenaars is an architect. He created the conceptual design for the building and is currently developing the technology required to realize the project in collaboration with BAM.

BAM
BAM is a large Dutch contractor. They are the contractor and investor of the project. They contributed to the technical development in the R&D phase and remunerate the involved actors in the project.

Acotech (AT)
Acotech is a Dutch robotics manufacturer. They had an indirect contribution to the project in terms of hardware and software. They provided supporting services in the software required to steer it.

Enrico Dini (ED)
Person that is responsible for developing D-shape, the technology on which the so called “3D builder” (the project’s 3D printer) is based. He had an active contribution during the technology development phase.

Hogeschool Amsterdam (HA)
Two interns from the Hogeschool Amsterdam contributed towards the system development phase and recorded the process. According to Jonker, they were a driving force in the project, though the exact nature of their contribution is unknown.

6. Do you know if there were any contracts installed between the involved actors? If so, between which actors?

The other organizations are remunerated by BAM, though Ruissenaars is the person who initiated the project.

Project activities

Activity Themes	**Applicable? (check box if applicable)**
Client themes	
Client actions	
Contracts	
Program of requirements	
Other:	
Design themes	
Architectural Design	
Interior	
Landscape	
Building physics & Acoustics	
Structural/Civil	
Installations	
Geotechnical	
Design integration	
Other:	
Project Management Themes	
Organization/process integration	
Information/communication	
Risk management	
Other:	

7. Can similar themes be identified for the project phases you mentioned? If not, what themes existed in the project?

The current stage is largely R&D. So far the project is not in a stage where detailed task descriptions for disciplines are available. The themes above are therefore not valid for the current state of the project.

8. Which themes required the most attention?

Fine-tuning all variables to optimize speed and performance of the created objects required substantial effort.

9. Was communication ad-hoc or planned?

Ad-hoc. There was close collaboration which was rather informal.

10. Was there a project manager installed to coordinate the process? If not, who coordinated the process in the project?

It would not be accurate to state the ad-hoc nature of developing the technology as project management.

2. Specific questions per lifecycle phase

This part contains specific questions on each previously listed lifecycle phase in the project

AM project phases

11. What was the goal and the key activities of each stage that was previously mentioned?

1 Initiative and Project definition (Goal: Create a conceptual design)
Conceptual design was created

2 Partner Selection (Goal: finding partners that can realize the conceptual design)
Organizations were approached that could realize the project

3 Technology development (Goal: Developing 3D printing technology so that the double curved surfaces can be constructed) so it can construct the double curved surfaces

Building the hardware (robot, nozzle)

Software tuning (programming, small test runs). For input the software by Enrico Dini was used. This was able for the robot to start printing when an stl file was inserted.

Calibrating System (through live tests)

Printing small blocks

Compressive and tensile tests on the blocks

Optimizing process (through testing optimal manufacturing parameters can be discovered, to maximize performance and speed)

12. Which actors were responsible for and contributing to these activities? (RASCI)[18]

Key Activity	UA	ED	BAM	HA	AT
Creating Conceptual Design	R				
Partner Selection	R		I		
Technology Development (all activities below)	S	S	R	S	
Building the Hardware	S	S	R	S	
Developing the Software	S	S	R	S	S
Calibrating System	S	S	R	S	
Printing small building blocks	S	S	R	S	
Compressive tests on material properties	S	S	R	S	
Optimizing process	S	S	R	S	

The activities were conducted in close collaboration between Enrico Dini, BAM and Ruissenaars. meaning no specific responsibility was allocated. Since BAM was the financer of the project, they are indicated as

[18] For the overall project, it is likely that more activities were done. Since BAM however was largely involved during the technology development phase, only these activities are mentioned.

"responsible". Two interns from the Hogeschool of Amsterdam also had a substantial contribution to this development, and Acotech provided software support for the robot.

3. Challenges

13. Can you give examples of organizational challenges that were encountered during the project? How did you deal with these?

There were challenges every day. A lot of new elements were introduced resulting in additional uncertainty. How to get all the equipment together, if parties delivered on time, integrating all pieces into a functional whole. The collaboration between the organizations went well.

There were also technical challenges, like the hardness of Dutch water which influenced the final composition of the objects. A disadvantage of Dini's approach is that the created objects becoming soft if they become wet. (when exposed to rain for example). In the Netherlands, this type of material is no longer within the legal framework. In Italy however this this material is allowed to be used.

14. How did you verify the strength/stiffness and stability of the structure?

Compressive tests ("Drukproeven") on the blocks.

15. What was the method of financing for the project (gift, co-financing, public funding, private investment)

BAM has invested in the R&D, though they are currently reducing this investment. At the moment they are looking for a client/investor who is willing to further realize the project.

4. Concluding questions

16. How do you think the process could have improved?

See printing as a means instead of a goal.

5. Other

Innovation in construction
Construction firms generally don't have R&D departments. They only start thinking about innovation when it is required for a project. This means innovation in construction is mostly a project specific activity.

Optimizing processes is difficult when client demands are constantly changing. Particularly for BAM utilities project requirements are unique and constantly changing, making it difficult to innovate within existing standard processes (often it is the suppliers that innovate their components). BAM prefers to have a large amount of standardized "components" which can be combined in creative ways to meet project demands. These components have been similar over the last 20 years and will likely continue to be so in the next 10 years. This makes it difficult to innovate within the construction industry.

Freeform vs Rectilinear printing
Dini prints with sand, water and magnesium oxide en chloride (binder jetting). This technology is very different from contour crafting, which BAM infra is currently involved in with TU Eindhoven. The difference however is that with this approach you cannot generate freeform shapes. Shapes it does produce can also be made with conventional manufacturing methods. People involved in that project are referring to the opportunities it presents in terms of speed. Jonker believes in the freeform capabilities, not in the contour crafting approach. Being able to add something unique prevents the need to compete on price.

Printing as a goal in itself, rather than a means to achieve project objectives
Most projects in which 3D printing is currently applied are because it is "hip" and that they want to be first. For the dragons described in the Great Pagoda project he see's clear advantages, because here it is a means (that was cost efficient) instead of a goal in itself. People using 3D printing as a goal in itself may be required to bring the technology forward, but it is not a sustainable business model. If printing is used solely as a goal, it dies out as soon as the "newness" of the first couple of examples fades off. An example is the edge, a very sustainable building by Deloitte with a BREEAM score of over 99% (best in the world). Originally it was 85%, but Deloitte wanted to have the most sustainable building in the world, for which they agreed to pay extra. The reason they were willing to invest more was because they were the first. Now, they would not do something similar. Jonker expects something similar will happen to 3D printed buildings where it is a goal in itself.

BAM's perspective is to create buildings with a high quality at low cost, therefore being more pragmatic. As soon as printing is a means that is more cost efficient or provides more value than traditional manufacturing methods for a project, it has value for BAM. Currently, it is not sufficiently mature to be applied on this scale.

Future development
Jonker thinks it will take a very long time for 3D printing to catch up with processes that have been optimized for tens (or even hundreds) of years. For specials (like statues or ornaments), that require a lot of labor, a niche market is very likely to emerge. For 99% of the elements however, probably not, making mainstream application unlikely.

When complex shapes are in demand, 3D printing could offer a solution, but then it should always be a means, never a goal in itself. There are certainly projects that require complex shapes to be generated in which new fabrication methods like 3D printing could offer value, like the new depot for museum Boijmans van Beuningen (see pictures below). Larger players and startups are more likely to look into 3D printing possibilities then a medium sized contractor (as these care primarily about production)