CHALMERS

Investigating the Usefulness of 3DP in the Construction Industry

A Case Study of NCC Construction Sweden

Master of Science Thesis
in the Management and Economics of Innovation Programme

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CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sverige 2015
Report No. E 2015:098

MASTER’S THESIS E 2015:098

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Chalmers Reproservice
Göteborg, Sweden 2015

Abstract

A challenge for incumbent firms is to absorb new technology that is being pushed into the market. Finding areas of application for a technology within the firm is not always obvious, since the firm by definition already uses established competing technologies. A new technology with promising potential is 3D printing (3DP). The aim of the study is to assess the potential and to find areas of application of 3DP at NCC. The study is done by conducting a case study of NCC, and focus has been on finding a problem that the new technology could solve. Finding a problem that 3DP could solve at NCC was found inherently difficult, since there is no obvious area of application for the technology. 3DP's maturity was assessed by investigating the current state of development of the technology. The state of the technological development of 3DP to print end-components is low especially in the context for the construction industry, while it is high for prototypes. The main problem in the early phases of a project that NCC issues that 3DP address is the ability to communicate. The data for the study was collected through a customer finding approach, developed by Steve Blank, and it consists of three cycles where hypotheses are tested. The main area of application for 3DP at NCC is to print prototypes for communicative purpose when negotiating and communicating within the early phases of projects where the complexity is high. A possible area of application for modularized bridges is also found, though only to present the overall concept of the bridge. The main limitation of this study is that the empirical data has only been collected from the division that sells and produces infrastructure projects. Future research about investigating the usefulness of 3DP in the construction industry could be focused on housing and development divisions within construction companies.

Acknowledgements

This thesis concludes our studies at the Management and Economics of Innovation master's program at Chalmers University of Technology. We owe several people who were involved in this thesis a big thank you. First and foremost, Anne Elerud-Tryde, thank you for all the support and guidance through the uncertainties and ambiguities of this project. Also, to our tutor at NCC Stefan Dehlin, thank you for your dedicated supervision and guidance. We would also like to give Christian Sandström and Ludvig Lindlöf a special thank you. To all the people working at the second floor at NCC in Gothenburg, thank you for all the insights in the construction industry and small talks during the coffee breaks.

Gothenburg, June 2015

Markus Bruus, Adam Johansson

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1. Introduction

1.1 Background

A challenge for incumbent firms is to absorb new technology that is being pushed into the market. Finding areas of application for new technology within the firm is not always obvious, since the firm by definition already uses established competing technologies. This becomes even more difficult if the new technology by nature lacks obvious demand and clear area of application.

This study is about such technology, where the technology is a solution to a so far unknown problem. The technology in question is 3D printing (3DP). A technology said to be a strong contender for the title of "the next industrial revolution". Despite its great potential, the need for 3DP is not obvious. Having a solution (3DP) but no identified problem or area of application can be a challenge for both firms in general, and incumbent firms in particular. Compared to e.g. a fuel efficient engine, or a cure for cancer, which has obvious need and area of application, 3DP lacks obvious demand in many cases. Unless the innovation solves a problem such as cancer or global warming, one have to make sure the innovation is something the customers or users are interested in buying. Therefore it is of interest to understand what kind of problems 3DP can solve and if there are any useful areas of application.

The investigation of this technology and its possible areas of applications is done through a case study of NCC. NCC is one of the larger construction companies within the Nordic region of Europe, with a total market share of 5 percent (NCC, 2014). The company consists of three divisions; industrial, construction and civil engineering, and development. The largest customer is Trafikverket (TV), who is the public procurer of infrastructure, such as train rails, bridges, and roads. The revenue of the company is 57 BSEK (2014) and employs 18 000 people.

This research topic is interesting since it lacks an identified problem. As described above, “having a solution rather than a problem” can be applied to 3DP within NCC, the case study firm. What this means is that there is an opportunity to purchase a 3D printer but there is no identified need or usage within the firm for it yet. This makes research on the topic useful both from the perspective of NCC and from an academic point of view.

The definition of 3DP used in this paper is “a process for making a physical object from a three-dimensional digital model, typically by laying down many successive thin layers of a material” (Oxford Dictionaries, 2015). The possibilities of industrial usage of 3DP applications are enormous. Leading authorities, presidents of countries and 3DP gurus are talking about an industrial revolution that will disrupt many of the conventional production methods that are used today (Basiliere, 2014).

One indicator of this stated hype is the Gartner’s annual hype cycles which can be seen below. A position on the hype cycle indicates great expectations of the technology (Basiliere, 2014). In line with this are statements made by Barack Obama, who in his 2013 state of the union addressed 3DP and stated that the technology “has the potential to revolutionize the way we make almost everything” (CNN, 2013).

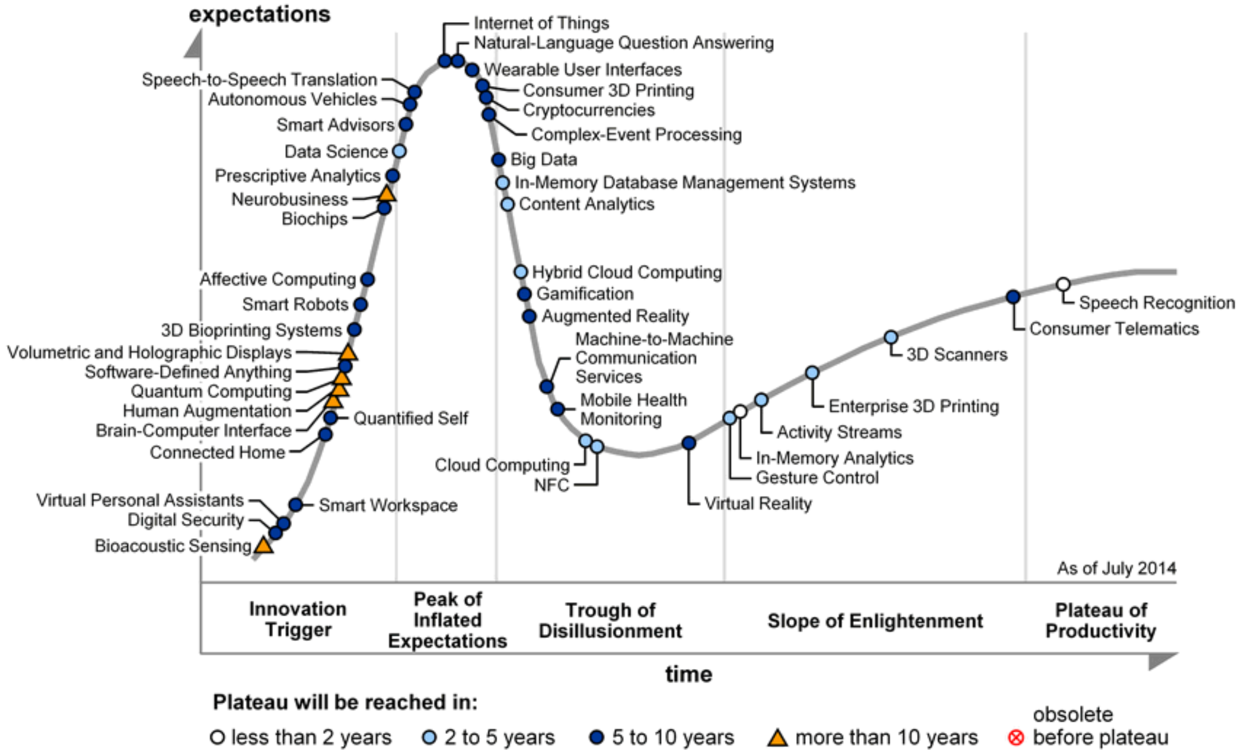

Figure 1, Technology Hype Cycle. (Basiliere, 2014)

One reason 3DP shows such potential is because anyone with the access to a printer and a computer is able to create a wide range of objects. These objects can be made by plastic materials, ceramics or metal. The objects are created in any 3D model software, such as Computer Aided Design (CAD), and “sliced” into thin layers. The layers are then printed out with a printer head, layer by layer (Schubert et al., 2013). These technologies are widely available due to a vast range of manufacturers popping up due to expired key patents during the last few years (Vinnova, 2014).

The market for 3DP grew by 35 percent during 2013, fuelled by the sales of under USD $5,000 "personal" 3DP:s (Wohlers, 2014). What can be achieved on a cheap desktop 3DP is not normally the same as what can be achieved on an industrial machine. The recent media hype around 3DP has tended to blur the distinction between the two (Vinnova, 2014). Many of the hyped statements mentioned are based on far reached advancements in the 3DP technology, and will not be realized within many years to come (Basiliere and Shanler, 2014). Thus, there is need to assess the maturity and readiness of the technology as of today.

When looking at present application areas in the building industry, limited usage is presented by Vinnova (2014) and here is limited research of 3DP in relation to the building sector. Present examples are in sectors such as hearing aid within the dental industry, lightweight components for the aerospace industry and prototype usage for the automotive industry (Vinnova 2014). Buswell et al. (2006) states that 3DP have been utilized by aerospace, automotive and consumer industries. Utilization of these methods within the construction industry is however limited but “is set to increase” (Buswell et. al 2006).

3DP is considered being on a hype, application areas within the construction industry are unknown and the readiness of the technology as of today is uncertain. These factor leads to a need of critically investigating the possibilities of using the technology. One method of identifying customers and users is proposed by Steven Blank (2007) in his book “4 steps to the epiphany”. This book is primarily used for start-ups that need to identify customers and making sure there is an identified need for the product they offer.

Even though the researchers of thesis does not represent a start-up, many of the fundamental principles Blank proposes can be attributed to the process of finding a use for 3DP within the case company of this study, NCC. The start-up is the researchers and authors of this paper, the product is 3DP and the potential market are projects, employees, units or anyone within the organization of NCC.

1.2 Aim

The aim of the study was to assess the potential and to find areas of application of 3DP at NCC. This was done by first analysing the current state of development of 3DP, followed by an analysis of how the main advantages of 3DP may help solve issues in the early phases of projects at NCC.

1.3 Research questions

1. What is the current state of the development of 3DP when applied to the construction industry?
2. What are typical problems in the early phases of projects, how does NCC address these and where is there room for improvement?
3. What is an area of application for 3DP at NCC, a large construction firm?

1.4 Limitations

This paper was conducted as a case study at NCC construction. NCC consists of three main business areas; industrial, construction and civil engineering, and development. This paper limits its unit of analysis to the construction and civil engineering business area of NCC. Furthermore, the report focuses on NCC in terms of usage of 3DP. There is no industry analysis, where NCC is compared to other firms in the construction industry. The 3DP technology is presented, but no analysis is done with regards to what kind of 3D printer is most suitable. Furthermore, the focus of the report is to assess the usefulness of 3DP as of now and thus there are limited speculations about the potential in the future.

2. Literature

In this section previous literature are presented and is divided into two main parts; first how to analyse a technology and its industry, and secondly a part about prototyping. The first part provides different points of view on how to evaluate a technology and its industry which helps at answering the first research question, regarding the maturity of 3DP. This is done by researching the life cycle of a technology, techno-economic analysis, technology push and technology pull, pro-innovation bias, technology readiness level, and technology readiness index.

The second part of the literature chapter is about prototyping and product development, which is a usage are for 3DP. First the dilemma between uncertainty and cost of making a change is presented, which is a recurring problem for all projects and product development projects. Finally, prototyping theory and how prototypes may address the stated problem are presented.

In order to get an overview of how the literature is connected to the respective analysis, table 1 presents which theory is linked to which analysis.

	Cycle 1	Cycle 2	Cycle 3
Technology Life Cycle (TLC)	X		
S-Curve	X		
Assesing technology usefulness (TRL, TRI)	X		
Pro-innovation bias	X		
Uncertainty of projects		X	X
Prototyping		X	X

Table 1, Overview of theory

2.1 Evaluating a technology that is being pushed into the market

A key question when a new technology, such as 3DP, is being pushed into the market is how to evaluate it, both in terms of how well developed the technology is today and what might happen with the technology in the future. Lindmark (2006) presents the technology S-Curve, which presents how certain parameter of a technology improve exponentially over either time or amount of effort. Knowing exactly where a technology is on a S-Curve would give great indication on how developed the technology is, however to ideally conduct such analysis either historical data or a longitudinal study of the improvement of one or several parameters would be needed. For this 6-month limited study, the concept of S-Curve is used, but indicators extracted from other analysis tools are used to determine where on the technology S-Curve. To be more precise, the output from TRL, which is more or less a cross-section of the development of the technology and gives an indication on how developed the technology is today, and essential elements of Technology Life Cycle, such as if the technology is an era of ferment or not and if a dominant design has emerged, is used to put the output from TRL in a context. Further, to speculate on how the technology can develop over time, TRIZ-laws are used.

Other concepts of the Techno-Economic Analysis (which S-Curve-analysis is a central part of), such as comparing the technology (3DP) with competing and complementary technologies (e.g. other prototyping techniques and virtual modelling) are also included. A part of this is done in the section about Rapid Prototyping and under the corresponding analysis in Cycle two.

2.1.1 General development of technologies – S-Curves

In order to understand how technologies and the correspondent economic benefit of using the technology evolve over time, a tool called Techno-Economic Analysis (TEA) can be used to "analyse and map the relations and interaction between technical and economic variables" (Lindmark, 2006:1). This section will provide an overview of the said tool with focus on the S-Curve. The applicability and level of abstraction of TEA may vary, and can be conducted on either national, industry, company, technology and/or product area level (ibid.).

The core of TEA is the S-curve. Compared to the previously mentioned technology life cycle, with a focus on number of manufacturers, product or process innovation, the S-curve on the other hand measures the technical performance over time. It is stated that evolving technologies follows an exponential curve of improvement. According to Lindmark (2006), the rate of change is dependent on the resources devoted and the respective marginal return. The development of the technology is exponential at the beginning, and as the technology reaches a point where improvements are no longer needed/possible due to physical constraints. For an example, the size of a mobile phone cannot be infinitely small and efforts in minimizing the size therefore decreases as the physical limit is reached. When a technology reaches this plateau, it is becoming vulnerable of being overtaken by a new technology (Christensen, 1992). The parameters of improvements are often size, complexity, efficiency, capacity, density and accuracy (Van Wyk 1984). In other words, S-curves can be followed along a number of different parameters, but the ones that are the most economical viable are of higher importance (Lindmark, 2006).

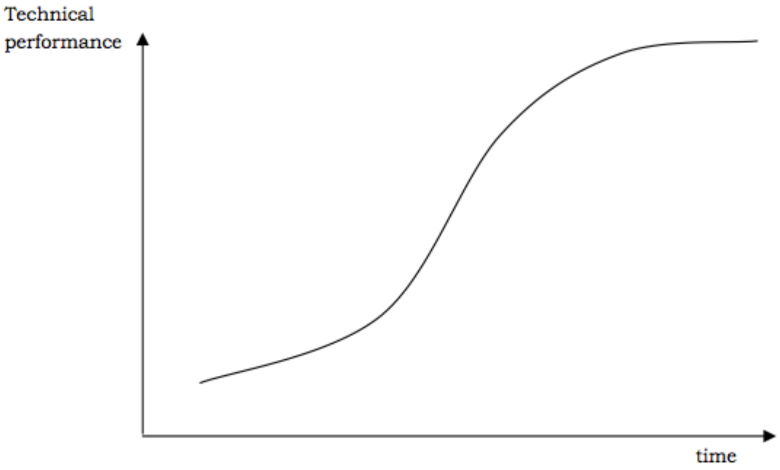

Figure 2, Technology S-curve (Source: Lindmark 2006)

S-curves are a powerful tool for technology analysis, but it is associated with limitations. Firstly, mapping technical performance in one dimension, such as speed or size, is not always enough to understand the development of a technology. Most innovations have to be measured against more than one characteristic (Lindmark, 2006). Due to the simplicity of the S-curve, it cannot always capture the general development of a technology (ibid.). Also, historical data about the development of the technology over a specific measure or a longitudinal study of said measure must be conducted to collect adequate data to plot an S-Curve .

Furthermore, a technology often consists of a system of different sub-systems, with correspondent relations and sub-functions (Lindmark, 2006). For a printer, this may be print head, print engine, drive gears, software and print controller. Improvements of each one of these subsystems is also subject to S-curve improvements. The improvements of each sub-system then adds up to an overall S-curve improvement trajectory for the whole system (e.g. printer). In addition, a technology system cannot be viewed in isolation, and the development of e.g. supporting infrastructure and the corresponding software ecosystem must be analysed. Lindmark (2006) concludes that “most technical systems are applied in a larger context where they interact with other technical systems and/or users” (Lindmark, 2006:11).

2.1.2 Technology Readiness Level – A cross-section analysis of the development

Mankins (1995) presents a framework called Technology Readiness Levels (TRLs) which is a systematic metric/measurement system for emerging technologies. This framework, which is originally developed by NASA, assesses the maturity of a technology on a scale from 1 to 9. Each TRL represent the development of a technology from a basic idea from a thought to the full deployment of a product in the market place. Following initial development by NASA other organizations, firms, and industries have used the TRL scale as a way to assess the maturity of a technology (Banke, 2010).

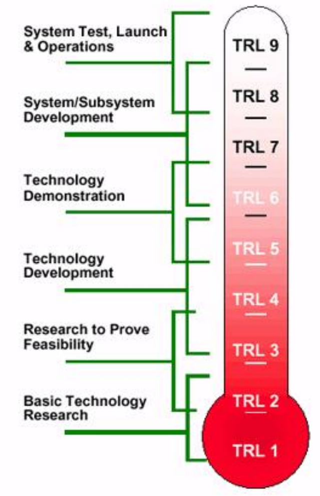

Figure 3, Technology Readiness Level. (Source: Mankins, 1995)

The lowest level, TRL1, indicates that a first step has been taken following scientific research. Basically, an idea has been generated about how to use the technology. For example, after learning that hydrogen and oxygen can be combined to generate electricity, TRL1 indicates that someone have an idea for building a machine to create just that (Mankins, 1995; Valerdi, 2004; Banke, 2010). The highest level, TRL 9 is a classification for a technology that has been fully incorporated and commercialized. It has also been proven to be fully operational and working as intended (Mankins, 1995; Valerdi, 2004; Banke, 2010). Another way of explaining the different levels of the scale is by looking at which actors on the market is involved with the development of the technology. The first three levels of TRL are basic research, primarily performed by universities. At level 4-7 research institutes are involved as well and industry end users involvement points to a maturity of around 5 or higher. Moreover, one can assess the level of readiness for 3DP from various points of views; TRL of a specific industry, TRL for a specific application area, and TRL for a specific material (Mankins, 2005).

Valerdi (2004) presents some critique of TRL; while the levels are useful methods for assessing technology readiness, they do not take any negative aspects of the technology into aspect. Thus, the TRL-framework seems to have an inherent pro-innovation bias since it does not include any negative aspects of the technology. Pro-innovation bias is a concept that describes decision makers' inability to see weaknesses and limitations of an innovation. By neglecting the negative aspects and consequences of an innovation the innovation is promoted regardless. Rogers (2003) explains that this kind of bias in innovation research as dangerous, since it under-emphasizes the need for re-invention or straight out rejection of some innovations.

In Sveiby's et al. (2009) article "Unintended and Undesirable Consequences of Innovation", they point to a 1983 innovation literature review by above-mentioned Rogers, who identified that only 0.2 percent of publications discussed the undesirable effects of innovation. When heading out to do a similar contemporary study, Sveiby et al. (2009) saw the need of a framework to map out these undesirable effects, hinting that research was still biased towards the desirable effects of innovation.

Pro-innovation bias in research might lead decision makers into choosing an innovation that is not fully developed or the best solution available. This is rarely discovered early but rather too late, when commitments have been made and a lock-in situation has occurred. In this case, the innovation might continue to thrive only because it is perceived as good (innovation for innovation's sake), while neglecting a better alternative or possibilities to re-engineer the innovation to make it better (Sveiby et al., 2009). When put into the context of 3DP, pro innovation bias would be to adopt the technology without assessing usefulness objectively. The concept of pro-innovation bias is therefore useful to keep in mind when assessing the capability of the technology.

Connecting the theory of Pro-innovation bias with 3DP, Basiliere and Shanler (2014) presents 3DP on a Hype Cycle, meaning there are great or even hyped expectations. Hyped Technology artefacts differ from other innovations and product launches because of all the buzz and publicity around it. And this hype impacts the adoption of technologies (Hedman and Gimpel, 2010). There is a need for critical evaluation of the readiness of 3DP. Thus, being aware of the inherent pro-innovation bias in the TRL-framework will give a more objective output of the TRL-analysis.

2.1.3 Technology Life Cycle

In the absence of a rich dataset of the development of a certain performance variable, analyses can still be made of the development of technology by looking at other factors. A common analysis tool in economics of innovation is Technology Life Cycle (Nelson and Winter, 2002).

This body of research explores the historical evolution of industries over time, often by looking at the development of technology and industry structure (Nelson and Winter, 2002). The aim is to identify whether there is a natural industry life cycle (Nelson and Winter, 2002). When a technology is new, there is a lot of uncertainty regarding the innovation, both regarding how the technology can improve and what the customers really want. This uncertainty leads to firms taking different directions and new firms may enter the field and other might leave due to wrongful choices and bad bets (Klepper, 1996; Nelson and Winter, 2002). This stage can be called the era of ferment (Cusumano et al., 2006). Eventually, one pathway or a set of pathways turns out to be more effective than the others. Furthermore, some products of this technology also start to attract a significant market. This pathway of superiority can be called the dominant design (Klepper, 1996). Firms who have chosen to invest in this design perform well and the other firms tend to fail. When the product design is primarily chosen firms shift their focus towards process innovations, researching and develop how the product is produced. This leads to fewer and fewer entrants and some very skilful firms in within the industry. Even as the output growth accelerates, due to process innovations, the number of firms decreases. A small number of firms end up dominating the industry. (Klepper, 1996; Nelson and Winter, 2002)

This description of a technology's life cycle provides insight regarding the variety and path dependence. During the early stage of a technology's life time, the number of players is usually high, before the major issues regarding design and technology remain unresolved. When a dominant design has been chosen, the natural selection is put at use, eliminating the weaker player and boosting the once left. The variety in these later stages of the industry life cycle is limited. The process is strong irreversible, meaning once a dominant design has been chosen, the choice is self-reinforced and a return to an earlier point in time is impossible (Nelson and Winter, 2002).

When applying this reasoning to 3DP one might look at the number of manufacturers, the variety in technologies to achieve 3D printed objects, the focus on product of process innovation, and other characteristics. This would then indicate where on a technology life cycle 3DP printing is positioned as of now.

2.1.4 The TRIZ-laws – Future Technological Development

In contrast to TRL, which only focuses on the current level of technological development, the bundle of TRIZ-laws may help predict how a technology may develop in the future. Which of the laws that are to be true are not clear, though one or some of them may become true at some point of the whole life cycle of the technology. The nine laws presented by Fey and Rivin (2005) can be summarized as the following:

1. Law of increasing degree of ideality
2. Law of non-uniform evolution of subsystems
3. Law of transition to a higher-level system
4. Law of increasing dynamism
5. Law of transition to micro-level
6. Law of completeness
7. Law of shortening of energy flow path
8. Law of increasing controllability
9. Law of harmonization of rhythms

The law of increasing degree of ideality is perhaps the most obvious one, since it states that the capabilities of technologies are increasing while the relative prices fall (ibid.). The law of non-uniform evolution of subsystems indicates that different elements in technological systems evolve at different phase (ibid.). According to Fey and Rivin (2005) this can create system conflicts. In the 3DP case, this could be that the prototyping technology does not evolve as fast as the detail level of virtual models. The third law, transition to a higher-level system, means that technologies can evolve to perform more tasks (ibid.). The fourth one, the law of increasing dynamism, states that structure becomes more flexible and that it can operate in a changing environment (ibid.). According to the law of transition to micro-level, large components are replaced by small molecules, ions and electrons (ibid.).

According to Fey and Rivin (2005), the law of completeness states that a technological system has four principal parts: working means, transmission, engine and control means. As the technology develops, the human interaction and component is eliminated. The law of shortening of energy flow path indicates that number of the energy transformations is reduced or that the number of energy parameters are reduced. The law of increasing controllability states that the system's different elements to a higher degree control each other. Finally, the law ninth law, indicates that the intra and inter communication of the elements of the system is coordinated so that they can easier talk with each other.

2.2 Prototyping

The following chapter will first present a recurring problem for all projects and product development projects, the dilemma between uncertainty and cost of making change, followed by prototyping theory and how prototypes may be used to address the stated problem. The reason to why prototyping theory is presented is because it is one of the two main areas of application for 3DP in the construction industry. The other main area of application, using 3DP to print end components, is researched in the previous section where the technical constraints and possibilities of 3DP are presented.

2.2.1 The dilemma between uncertainty and costs of making change

In any project or product development process, there is a trade-off between the uncertainty of what changes to make and the cost of making a change to the product (Verganti, 1999). This means, as the time progresses the amount of information and insights about the customers' wants increases, although the cost of making changes increases exponentially (Gebhardt 2003). Verganti (1999) investigated differences between high and low performing product development projects and found two key factors to a successful project; anticipation and reaction capabilities. The anticipation capabilities are the project team's capabilities of anticipate information in the early phases of a project (Verganti, 1999). The early phases of a project is crucial to the overall performance, since many of the crucial decisions are made in these phases and cost of corrective actions later on are usually high. The reactive capabilities are the capabilities of effectively introduce changes in the later phases of a project (Verganti, 1999).

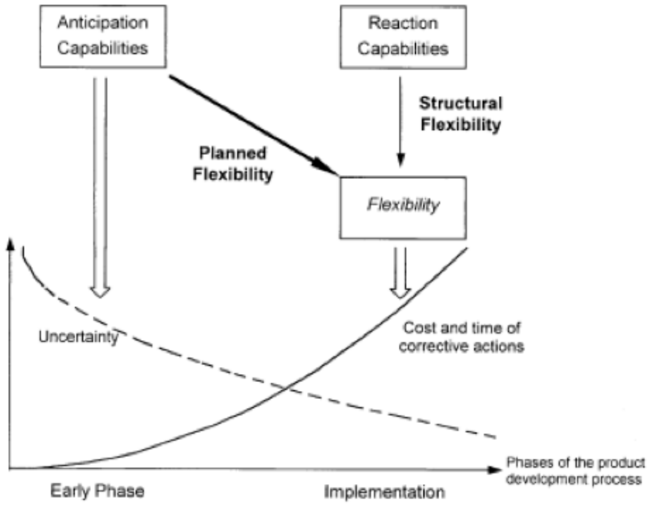

Figure 4, Trade-off between uncertainty and costs of making change (Source: Verganti, 1999)

Verganti (1999) found that the anticipation skills are dependent on three variables:

1. Systematic learning (the mechanisms and ability to learn from past projects)
2. Teamwork and communication (the early involvement of all major actors having a direct contact with future constraints further on during the project)
3. Supported proactive thinking (the use in the early phases of different checklist, failure and effect analysis and early prototyping)

Thus, by improving these variables the anticipation skills increase. As a consequence, the performance of the overall project also increases, according to Verganti. On the other hand, if one wants to find a relevant problem, these variables could be examined.

2.2.2 Roles of prototypes

In this section, the roles of prototypes in project in general and product development projects in particular will be presented. Several different roles of prototypes can be identified, but only three are presented here. A selection of the different roles of prototypes was made because they are outside the scope of this thesis. The three roles are learning, communication, integration (Ulrich and Eppinger, 2012).

Prototypes as a learning tool

Elverum and Welo (2014) states that prototyping is particularly of interest when the product development team wants to explore various concepts and reduce technical uncertainty. In other words, prototyping can be used to test different types of a product, and serve as a tool to more rapidly decide which concept to take further in the process. Deciding which concept to continue developing throughout the process is an inherently difficult problem that prototypes may partly solve since they provide the developers with detailed characteristics of the end product.

Barkan and Lansit (1993) claims that it is mainly in the early stages of the product development the aspect of learning comes in. Diverse points of view must be collected and tests are performed, while the design is still flexible. Once information from diverse points of view are collected and included in the product, the process can be iterated (ibid.). This way, information and input from other people are internalized into the product rapidly, and the new changes can directly be verified and validated.

Prototypes as communication tools

Having a physical prototype may help the innovator or team to deliver a proof of concept, both to colleges and upper management. Delivering an early proof of concept to upper management may increase the funds given to the project (Liou, 2008). Elverum and Welo's (2014) confirm Liou's statement and claim that prototypes are the most effective method when convincing internal decision makers and external stakeholders. Thus, prototypes have a role as communicating tools. Prototypes can also be used when interacting with customers, and validating their requirements (Liou, 2008).

The reason to why physical prototypes are good communication tools is that such prototypes are easy to understand for people who are not technically versed, such as customers, upper management and other stakeholders. Thus, prototypes solve problems in communication in general, and problems in the communication between people or groups that uses different terminology.

Looking at visual management literature, which both virtual and physical prototypes are subsets of, further theoretical findings can be made. In general, According to Lindlöf (2014), visual management can be divided into communication of tasks and communication of concept and design. Visualization may help support human's cognitive functions, which has potential for managerial tasks. Visualization is today extensively used to communicate technical properties through among others CAD and 3D-models (ibid.). Though, visual management may also help support an organizations information processing capabilities by handling uncertainty and reducing ambiguities (ibid.). Thus, there is a distinction between visual management that help communicate technical properties and visual management that may help reducing uncertainty and ambiguities. CAD and 3D-models may very well help preform the latter one, but it is not excluded that other types of visual tools may be better suited. Also, Lindlöf (2014) stresses that visual management play an important role in supporting communication between individuals, where he points out that visual management help trigger synchronous and rich communication. This is especially true for when individuals have different perspectives, knowledge and agendas (ibid.).

Prototypes to facilitate integration

Prototypes serve different roles during different parts during a product development process. Prototypes that have an integrating role are generally more comprehensive and used at the end of the process, in order to ensure that all subparts fit together as expected (Ulrich and Eppinger, 2012). Prototypes may also serve as a lubricant when integrating different points of view in a team (Ulrich and Eppinger, 2012; Leonard-Barton, 1991).

2.2.3 Different types of prototypes

There is a wide range of prototypes that has different purposes. First, there are two main types of prototypes, analytical and physical. Analytical prototypes are used when the product or element is to be tested, virtually simulated and analytically analysed. These types are often computer models that exist in software programs. Physical products can either be a full scale version of the final product or a miniature (or a scale-up). Physical products can further be broken down to focused models, form models, alpha prototypes and beta prototypes. Focused prototypes only display one or a few variables of the final product, e.g. the height and length. They can either exist in physical or virtual form. Also, before using a certain prototype, objective of using it should be defined (Liou, 2008).

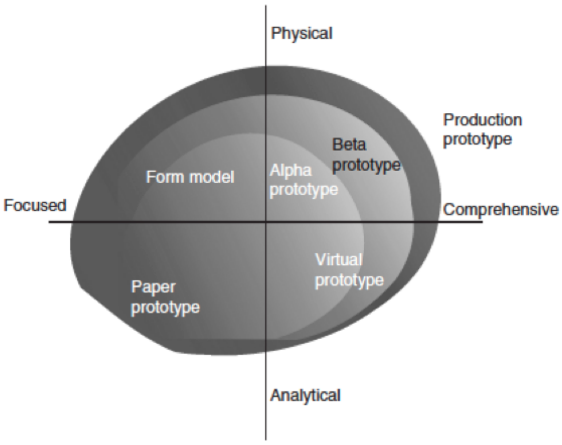

Figure 5, 4 Different types of prototypes (Source: Liou, 2008)

The alpha prototype is used internally, when all the individual sub-elements of the product is proven to work. An alpha prototype does not necessarily have to be in the same material as the final product, in contrast to the beta prototype. According to Liou (2008) the beta prototype are given to customers or focus groups in order to detect final design flaws. An underlying assumption in Liou's reasoning that is not explicitly stated is probably that he has traditional product development in mind, and not necessarily product development in construction projects where the customer is highly involved early on.

Analytical prototypes	**Physical prototypes**
Generally more flexible	Not flexible, iteration is needed in order to change design
Cannot reveal phenomena that is not included in the underlying analytical model	Can detect unanticipated phenomena, such as thermal, optical, or electrical-mechanical couplings.
Can be used to narrow the range of feasible parameters	Can be used to fine tune or confirm a design

Table 2, Differences between analytical and physical prototypes. (Source: Simplification of Liou, 2008)

Another difference between analytical models and physical models is that people tend to learn more in a shorter amount of time when using a physical prototype (Liou 2008). As earlier discussed, this has effect on the speed of the product development process and using physical prototypes as communication tools.

Combining the chapter about the purpose of prototypes with the description about the different prototypes, the following table (table 3) unfolds.

	Learning	**Communication**	**Integration**
Focused Analytical	X		
Focused physical	X	X	
Comprehensive physical	X	X	X

Table 3, Roles of prototypes versus types of prototypes (Source: Liou 2008)

Common mistakes using prototypes

Using prototypes during the product development process is not only one-sided positive. Some drawbacks with using prototypes can be identified.

The product development team may commit to a particular design too early, developing a suboptimal prototype. To mitigate this, it would be wise to create several different prototypes at an early stage. Prototypes may also mislead internal (decision makers) and external stakeholders (customers), since the materials of prototypes are different from the actual products. Furthermore, it is generally hard to know when to stop iterating. To mitigate this, purpose and clear goals should be defined before one start to creating prototypes. (Liou 2008)

2.2.4 3DP (or rapid) prototyping

There are several advantages of using 3DP prototypes, compared to other physical prototyping techniques. Other prototyping techniques could be crafting of wood, papier mâché or injection moulding. The most obvious is the easiness of iterate and reprint a refined prototype. The 3DP prototype is generally packed with higher functionality, such as with moving parts and with different colors. There is also a possibility for the engineers and designers to work together and concurrently improve the design and functionality of the product (Lipson and Kurman 2013).

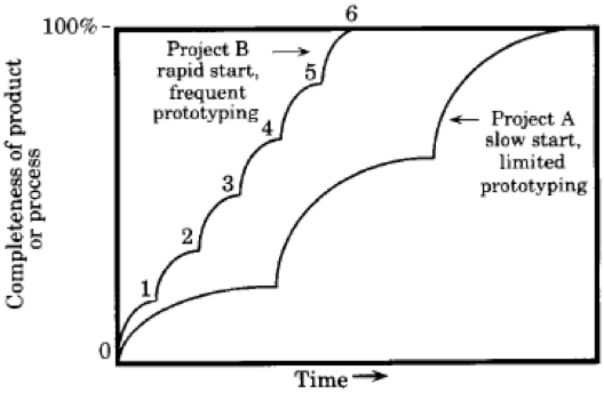

Figure 6, Iteration cycles. (Source: Liou 2008)

There is much to gain by frequently iterate and to internalize the knowledge gained as quickly as possible (Barkan and Lansit 1993), see Figure 8. In order to frequently iterate the physical prototype, there is a need for a low cost fast prototyping process, such as using 3D printers.

Objects with high geometric complexity can be produced fast to a low cost. Different materials can also be used, depending on the printer. A key aspect with 3D printers, especially for companies who uses CAD models as analytical prototypes, 3D printed prototypes can be used to verify the CAD data and help detect errors with the CAD model. Misaligned holes, interferences, structured ribs that are in the wrong place can also be detected.

2.3 Reflection of theory

Nelson and Winter (2002) and Keppler (1996) provide life cycles that are of interest when assessing the maturity of a technology. The pattern is that when a technology is new, there are multiple firms competing with different versions of the technology. One tends to speak of an era of ferment before a dominant design has been settled. Applying this analysis to 3DP is possible by looking at number of firms, if they focus on product of process innovation, and if there is a present dominant design yet.

Furthermore the development of a technology can be done by a Techno-economic analysis, provided by Lindmark (2006). The core of TEA is the S-curve. It is stated that evolving technologies follows an exponential curve of improvement, which can possibly be used to assess 3DP. Furthermore, the technology cannot be assessed on its own, 3DP is closely linked with the development of subsystems such as computers, materials, and computer aided design software (CAD). The improvements of each sub-system then adds up to an overall S-curve improvement trajectory for the whole system. Criticism against S-curves is that they map a single technology versus a single trait, such as speed or size. However, most innovations have to be measured against more than one characteristic. 3DP may not be an exception to that, meaning they rely on many simultaneous developments. This may therefore limit the usefulness of using an S-curve to explain patterns regarding 3DP.

The message provided by Swann (2009) is that innovation cannot be demand-pull or technology-push alone. We must have both working together before an innovation will take off (Swann 2009). This reasoning can be compared to the case of 3DP. There is an existing technology but no identified demand within NCC. For innovation to take off there needs to be an identified demand as well.

Furthermore, the TRI framework is presented to understand the organization's readiness. As a hypothetical case; If readiness at NCC is assumed to be low, then usage rates would remain low regardless of high sales of printers. I.e. it would be high penetration, while the actual usage of the printers would remain low. Therefore, the readiness for NCC to use 3DP is interesting to investigate.

There seems to be an underlying assumption that prototype theory is based on conventional product development theory, which is most often applicable for development of traditional consumer goods. Thus, there is a discrepancy of applying prototyping theory for construction projects, which most often has a higher customer involvement in the early phases of a project. An example of this is the theory about the different types of prototypes, where the theory explicitly states that feedback from possible customers is gained at the end of a product development project when presenting the alpha and beta prototype. Thus, the usage of prototypes in construction projects is a rather unexplored area of research.

3. Methodology

3.1 Research Design

As basis for the choice of research design was the lack of an identified customer with a clear problem. The research was therefore designed to find one or several customers with a problem that the solution (3DP) would solve. Due to the explorative nature of the aim, a qualitative approach was decided appropriate. Within the boundaries of the qualitative approach, a case study was performed. The structure of collecting data within the case study was largely influenced by Steve Blank's (2007) customer finding approach. Further details on how the study was conducted, why the chosen design was deemed appropriate along with presentation of the unit of analysis will be presented in the following paragraphs.

In general, a research can either be quantitative or qualitative. A qualitative research is defined by Strauss and Corbin (1990:17) as "any kind of research that produces findings not arrived at by means of statistical procedures or other means of quantification". Thus, qualitative research seeks to find an understanding and illumination, while quantitative research seeks to find causal determination and generalization of findings. In this study, the data collected was nearly exclusively qualitative because the researchers aimed to find one or several areas of application for a new technology, a rather exploratory field of research.

A case study is appropriate when one wants to look in depth into one, or a few, organisations, events or individuals over time (Easterby-Smith et al., 2012) and is suitable when the research questions seek to explain a present circumstance (Yin, 2013). Thus, a case study within the setting of a qualitative approach was used. Moreover, a case study entails the detailed and intensive analysis of a single case (Bryman and Bell, 2011). Since the aim with the study was to find an area of application for a new technology (in an organisation), a company that does not utilize the new technology as of today was decided to suitable as the case for the study. The initial unit of analysis was the technology, 3DP, and the company, NCC.

Yin (1994) states that a case study should follow the following four steps.

1. Designing of the case study
2. Conducting the case study
3. Analysing the case study
4. Developing conclusions and recommendations.

The recommended, and rather intuitive, four stages was followed. The designing of the case study is done by first determining the required skills and data that needs to be obtained by the study. At this stage, the problems of identifying the proper data were brought up. Since the researchers at the time could not pinpoint exactly what type of data to obtain, the customer development process was decided to function as a framework for data collection. In the second stage, three tasks need to be done in order for the research to be successful. These are preparation for data collection, distribution of the questionnaire and conducting the interviews (ibid.). All three tasks were performed within the setting of the customer development process. The fourth step is the analysis of the case study, which is where one summarizes and synthesizes all the gathered information. The analysis of the results was made with a systematic combining approach. The last stage, developing conclusions and recommendations, was aimed both at for the focal organization and for future research.

In order to successfully complete a case study, there is a need of thick descriptions. For this research this includes data about the technology readiness of 3DP and descriptions about possible problems that 3DP could solve. This means that there should be much information, in-depth description of the phenomenon, context, characteristics of people, particularities and circumstances (Yin, 1994). In addition, to gather valid information the case study needs to be based on a literature review since a lack of pre-understanding will cause the researcher to spend considerable time gathering basic information that will not enable any analysis (Meyer, 2001).

3.1.3. Data Collection

The general framework for data collection of this study was the Customer Development Process developed by Steve Blank. As a consequence, nearly all collected data is data retrieved from interviews. The Customer Development Process was chosen of several reasons: first and foremost, the researchers could not pinpoint which type of data that needed to be collected when the case study was designed. The process also fits well with the problem of having a solution, but not a clear customer with a clear problem that could be solved with the 3DP technique. The process also relies on qualitative data, which already had been decided to be suitable for the setting of the study. Furthermore, the process also fits well within the boundaries of a case study.

The Customer Development Process

The Customer Development Process was developed by Steve Blank in 2007 and was developed to help start-ups finding the right customers. As many start-ups are focus on developing their technology and focus little on developing customers, the aim of this method is to develop the right customers.

Blank states that most start-up do not fail because they fail to develop a good product, they fail because they do not develop the right customers. The method recognizes that process of finding the right customer is inherently unpredictable and that the start-up owner will “screw up several before he/she gets it right…//…it is ok to screw up if you plan to learn from it” (Blank, 2007). The method also embraces that the aim of the whole process should not only be about finding customers, but finding customers with the right problems. Thus, the process contains two goals: finding customers, and finding problems that the product or service could solve.

Blank’s method can be divided into four different steps, see Figure 7. For this thesis, the focus will be on the first two steps. Essential in the customer development process is that each step is iterative.

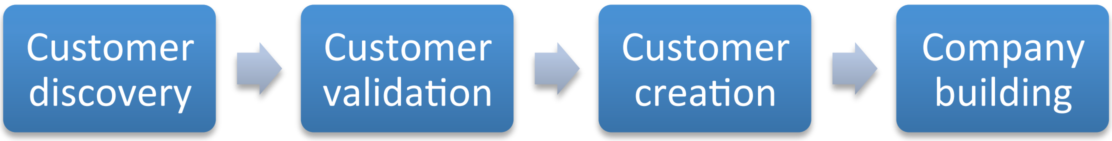

Figure 7, The Customer Development Process. (Source: Blank, 2007)

The first step, customer discovery, is the process of finding potential customers with the corresponding problem that the product/service aims to solve. A key to success is to find out whether the problems that the product/service aims to solve are important to the potential customers. The process in the second step, customer validation, is about building a repeatable sales road map for the future. In sum, the first two steps verifies the market, locates the customers, tests the perceived value and identifies the economic buyer, and is iterated until a scalable sales and customer model is repeatable. It is important to understand the needs and wants of all customers, and to realize the one should not develop a product for the many, but for the few in a start-up.

Mapping the concepts of this method on the process of finding a possible area of application of 3D-printers in a Swedish construction company, the customer is NCC or more to be more precise; one or several divisions/teams/projects/product groups at the company. The “start-up owner” is the researchers, and the product 3D-printing technology.

3.1.4 Modifying the Customer Development Process for this research setting

The researchers for this study used the general characteristics of the Customer Development Process, but used the criterion checklist presented by Brians et al., (2011) as the basis for hypothesis generation. After each cycle, the hypotheses are either rejected, revised or believed to be worth further analysing in the next cycle, in accordance with Blank’s process. To further structure this rather explorative and flexible research design, study questions were formulated at the beginning of each cycle and were used as a guiding too. To clarify, neither the number of cycles are predetermined, nor the specific method that were used in each cycle. Hence, the study was highly explorative and flexible.

The first hypotheses were broad and general, where the usage of 3DP was primarily investigated from a top-down perspective. During these cycles more effort were put on industry reports and academic research. But as the study progressed, the narrower the hypotheses became and potential users were specified and interviewed.

	Cycle 1	Cycle 2	Cycle 3	Cycle 4
Academic research	Yes	Yes	Yes	No
Industry reports	Yes	No	No	No
Interviews academia	No	No	Yes	Yes
Interviews NCC	Yes	Yes	Yes	Yes
Interviews at TV	No	No	No	Yes

Table 4, Type of Interviews.

The Customer Development Process also contains the method of using working hypotheses, although the framework for hypothesis testing in Blank’s method is not entirely suitable for this research setting. As basis for hypothesis creation, Brians' et al., (2011) framework was used instead. Brians et al. (2011:29) states three characteristics that a hypothesis should include, these are:

1. “Are declarative sentences”
2. “Identify a relationship (often a directional relationship)”
3. “Are specific”

Shields and Rangarajan (2013) explains that the declarative nature of a hypothesis stems from the answer-question dynamic, where a hypothesis is an answer the question. Students often confuse the answer-question dynamic and forms hypotheses as questions instead (ibid.). Since a question may have many different answers, it is possible to generate several hypotheses when trying to answer one question.

The second characteristic exists because hypotheses often try to answer a "why" or "what causes" question (ibid.). The direction of the relationship may be presented in the hypothesis if there is an obvious causality between different variables (e.g. taxi fare price and distance driven) (ibid.). If no obvious causality can be found on beforehand, the direction does not need to be presented (e.g. political party and church affiliation).

The more specific a hypothesis is, the easier it is to test it (ibid). It is important the hypothesis is uncluttered, meaning that no underlying assumption or information should be included. The hypothesis should also be concise (ibid).

3.1.5 Structure of interviews

According to Easterby-Smith (2012) there are three types of interviews, highly structured, semi-structured and unstructured ones. Highly structured interviews are having a predetermined set of questions which the interviewees does not deviate from during the interview. Using predetermined questionnaires are useful when the interviews wants to have answers to reasonable simple questions and when interviewing several different persons. When conducting semi-structured interviews the researchers should be prepared by having a topic guide and/or a checklist. During semi structured interviews, it is also possible to discard some topics and add other ones as the interview proceeds. When moving further to the completely unstructured interviews, the researcher should try to find stories and he/she should not try to limit the interview on beforehand with too specific topics. (Easterby-Smith, 2012)

For this study, there was no uniform usage of interview type although the majority of the interviews conducted were semi-structured. Each interview was planned carefully and the decision of level of structure was determined before each interview, rather than at beginning of the whole study.

	Firm	**Position**	**Length and number of interviews**	**Recorded or not.**	**Cycle, and focus of interview**
1	NCC	Director of Research and Development	Multiple brief interviews	Not recorded	1, formulate research problem,
2	NCC	Technical Specialist	Multiple interviews	Not recorded	1, formulate research problem,
3	NCC	Senior Project manager R&D	1 hour	Not recorded	1, identify application areas
4	NCC	Manager of the internal consulting	30 min + 1 hour	Recorded	2, develop hypothesis

		group			
5	NCC	Technical specialist infrastructure	1 hour	Recorded	2, develop hypothesis
6	NCC	Director production development, NCC construction	45 min	Recorded	2, develop hypothesis
7	NCC	Construction Site Manager	1 hour,	Recorded, telephone interview	3, test hypothesis
8	NCC	Contract Manager	1 hour	Recorded	3, test hypothesis
9	NCC	Site manager of previous projects with modularized bridges	30 min	Not recorded, telephone	3, test hypothesis
10	LTU	PhD Student, Industrialized Construction	2 hours	Recorded	3, develop hypothesis
11	CTH	PhD, Visual Management	1 hour	Not recorded	3, develop hypothesis
12	CTH	PhD, Industrial doctorate at NCC, Visual Management.	1 hour	Not recorded	3, develop hypothesis
13	Trafik-verket	Project leader BIM	1 hour	Recorded	3, test hypothesis
14	Trafik-verket	Procurement, Head of contract formulation	1 hour	Not recorded	3, test hypothesis
15	Swere a IVF	3DP researcher and consultant	2 hours	Not recorded	1, explore TRL of 3DP.
16	NCC	BIM coordinator	30 min	Not recorded	Identify usage areas for 3DP prototypes
17	NCC	Technical Specialist	30 min	Not recorded	Identify usage areas for

					3DP prototypes
18	NCC	Group Manager Construction	30 min	Not recorded	Identify usage areas for 3DP prototypes
19	NCC	Technical Specialist	30 min	Not recorded	Identify usage areas for 3DP prototypes

Table 5, Conducted Interviews

3.1.6 Systematic combining - an abductive approach of analysing the collected data

Using an iterative research process such as the customer development process is not entirely new in a research setting. Dubois and Gadde (2002) presents a framework based on systematic combining between theory and data. Their starting point is that most textbooks on research methodology describe case studies as a linear process, with pre-existent categories and ideas. Systematic combining between theory and data (and vice versa) rather develop categories and ideas from the data.

The researchers of this study embraced the findings of Dubois and Gadde (2002) and used the customer development process as a tool to practically execute the theoretical framework developed by Dubois and Gadde. By systematically and iteratively combining theory and data at the end of each cycle, conclusions (or hypotheses) were developed by the end of each cycle. In line with the researcher's use of the customer development process, Dubois and Gadde (2002) states that the case evolving during a study can be regarded as a tool or product, and the aim with the case study becomes a process of the sharpening of this tool or product, which is interpreted as a justification to use the customer development process. Also, Dubois and Gadde (2002) claim that the tool or product cannot be planned in advance, but is rather developed during the case study. Thus, the method and topics investigated in each cycle is not planned on beforehand, but rather at the beginning of each cycle.

3.2 Sampling of areas of application

Throughout the study, different areas of applications are found. The sampling of these is dependent on the application areas presented by respective interviewee. This means that the sampling of cases has neither been done in a random nor objective fashion. The approach, however, was decided suitable since a complete presentation of all areas of application is out of scope for a master thesis.

3.3 Validity of the study

There are several types validity related to academic research. Validity is associated with measuring what is relevant in the context (Bryman and Bell, 2011). In this section, internal and external will be discussed.

The exact method for the whole study was not predetermined at the beginning of the study, but at the beginning of each cycle. Thus, each cycle could easily be replicated and done by other people in similar setting, but the study as a whole has rather low repeatability. Each cycle followed the finds in the previous and the path for this research may not be the same for another study using similar methodology.

The external validity is the extent to which the results of a study can be generalized to other situations and to other people (Easterby-Smith et al., 2012). It is important to make a distinction on what elements and parts of the method that can be subject to a discussion about their respective external validity. Though looking at the big picture, the methodological approach of exploring and expanding the personal knowledge base in one or more subjects that are unknown on beforehand has high external validity. The study firm is NCC and the results regarding applications areas may be generalizable to other construction firms with similar operations, since the construction industry arguably works in similar ways. The assessment of technology readiness for the construction industry is based on a more general reasoning and this reasoning possesses a higher external validity compared to the previous mentioned application areas.

The internal validity is high, since no little room for confounding and mistakes can be found. In line with this, the reasoning of the interviewees represents the view of the organization of NCC well.

4. Empirical findings and Analysis

Each cycle follows the same systematic design, though different methods have been used. The start of each cycle is one or several hypotheses on which study questions are being. Depending the purpose of the cycle, academic theory and/or own collected data in order refine the hypotheses. At the end of each cycle the findings were summarized and the hypotheses refined. After the hypotheses were refined, the most promising ones were used as input hypotheses into the next cycle.

4.1 Cycle 1 - Exploring the technology readiness of 3DP

4.1.1 Initial Hypothesis

- The 3DP technology has enough readiness to be used either for end components or prototypes (to be tested)

4.1.2 Study questions

1. What is the readiness of the 3DP technology for end component usage, and for prototype usage?
2. Are there any other external factors, such as regulatory ones, that could affect the possibility of implementing 3DP?

4.1.2 Empirical findings

The Empirical Findings contains two main parts; background of 3DP, and empirical findings of NCC regarding limits and constraint of its products.

The first parts aim at providing an overview of the technical possibilities and constraints with 3DP. The description of the technology behind, the history, and the present use of 3DP are presented. furthermore, the found benefits and identified limitations are analysed to give a realistic standpoint of the technology's usefulness. This is provided first by literature and industry reports and it is being followed by an interview with 3DP consultant working at Swerea IVF, a research institute in Mölndal, Sweden.

The second part is empirical findings of the construction industry in general and of NCC. Here the organization is presented and the limits and constraint their products and components must adhere to.

Definition of 3DP

3DP is "a process for making a physical object from a three-dimensional digital model, typically by laying down many successive thin layers of a material" (Oxford Dictionaries, 2015:). Just like an inkjet printer placing ink in a single layer on a paper, a 3D printer successively places several layers of various materials on top of each other, which results in a 3D object.

The process of creating an object using 3DP begins with a 3D model of the object, usually created by CAD software or a scan of an existing artefact. Specialized software slices this model into cross-sectional layers, creating a computer file that is sent to the 3DP machine. This machine creates the object by layer-by-layer building the object (Campbell et al., 2011; Bogue, 2013; Berman, 2012).

Today's hype of 3D printing is primarily due to multiple numbers of 3DP patents that has been expired, which has massively increased the number of 3D printer manufacturers (Hornick and Roland, 2014). It was the expiration of some Fused Deposition Modelling patents, such as U.S. Patent No. 5,121,329 to Stratasys Inc., which created a boom of growth in the consumer-level 3D printing industry. This has led to machines that previously cost thousands of dollars now cost hundreds (Hornick and Roland, 2014).

3DP as a technology was invented in the late 1970s (Thomas, 2014). A few years later, in 1984, Chuck Hull of 3D System Corporation developed the first prototype system, which was based on stereolithography, which is one of the total of three technologies that make up the concept of 3DP (The Economist, 2013). Since then the development of the two other 3DP technologies have been added. Throughout the years, various terms and names of 3DP have been used. Examples are Rapid Prototyping and Rapid Tooling. They use the same technology, 3DP, but are called differently since they have different purposes. Rapid Prototyping is the ability to print a prototype in a simple shape and material and it was developed during the 1980s and 1990s. Rapid Tooling, the technique of creating tools of casts out of rapid prototyping technology, came just a few years later. Rapid Manufacturing is the name for the method of creating end products using 3DP technology (Boivie, 2013).

In addition to the terms above, there are multiple terms associated to 3D printing. Layer-by-layer manufacturing, layer manufacturing, additive manufacturing, are all variations of 3DP. Petrick and Simpson (2013) argues that 3DP and additive manufacturing are often used interchangeably and that both refer to layer-by-layer creating of physical objects based on digital files in a computer. According to Boivie (2013) 3DP is a very popular term, but other popular use is rapid prototyping and rapid manufacturing. Arguably, all these terms are different names for the same technology. That there are many terms for describing the same technology is unfavourable. A European standard for naming and classifying 3DP is being developed (Kristiansson, 2014). As of now, the authors of this thesis believe that 3DP is the most well-known term for this technology and this term will therefore be used throughout this thesis.

Three different 3DP technologies explained

3DP is an umbrella name of three different technologies. What each of these three technologies has in common is that they create objects layer-by-layer. The difference is that they achieve this in different ways, either using filament, liquid resin, or a powder bed (Dezeen 2013). The three 3DP technologies are:

- Fused Deposition modelling (FDM)
- Sintering
- Stereolithography

The first technology, FDM, is considered the most basic technology and uses a plastic filament. This filament is fed into a nozzle that heats the filament until it becomes semi-liquid. This liquid is then distributed to a platform layer-by-layer to manufacture the object. This 3DP technique works similarly to an inkjet printer. The print head, which is fed with filament, moves in X- and Y-coordinates, depositing material to complete each layer before the base moves up along the Z-axis. When the base has moved downwards the next layer can be applied. This process is illustrated in Figure 8 below. This technology is the most basic in terms of available materials.

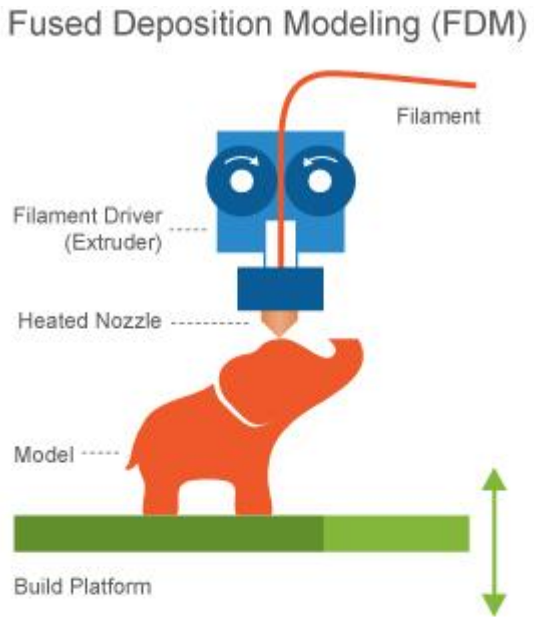

Figure 8, Visualization of the FDM technology, which uses filament. (Source: Spadaro, 2014)

The FDM technology was invented in the late 1988 by Scott Crump who established the firm Stratasys to commercialize the technology. Stratasys is together with 3D Systems one of the two largest manufacturers of 3D printers as of today. Even though FDM is one of the three basic technologies that make up 3DP, many printers using the technology are labelled differently. Because the term fused deposition modelling (FDM) is trademarked, other manufacturers may call their versions of FDM “plastic jet printing”, “thermoplastic extrusion” or “fused filament method” etc. (Bogue, 2013).

FDM has, due to a number of expired patents, become a very popular technology for consumer based 3D printers. 3D printers targeted towards consumers are exclusively using FDM technology (Dezeen, 2013). FDM drives the total growth of 3DP sales. This is the case since FDM (or any version of it) is the technology every consumer based printer uses (Basiliere 2014).

The second of the three basic 3DP technologies is Stereolithography. This technology is visualized in Figure 9 below. Printers using this technology have a perforated platform located beneath a container of a liquid UV-curable polymer. It is this polymer that will make up the 3D printed object. A laser beam is applied to the liquid, making a hardened slice of an object on the platform. The platform is lowered and a new slice is cured by the laser which leads to the making of a 3D object. This technique can vary depending on what optical method you use. There are 3D printers using electron beams or UV laser of digital light operating at UV wavelengths (Bogue, 2013).

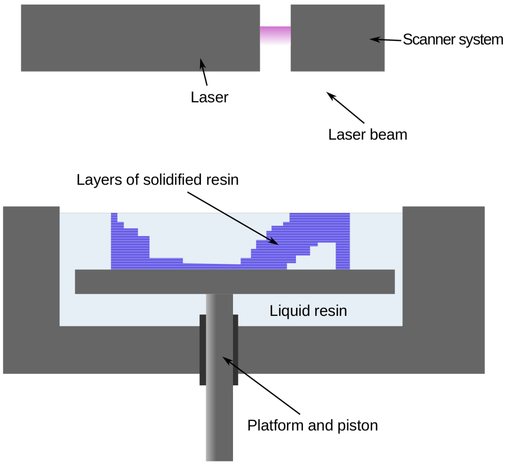

Figure 9, Visualization of the Stereolithography technology, which uses a liquid resin. (Source: Wikipedia, 2015a)

The third technology called Sintering, involves selective bonding of powdered materials. This technique uses heat to bond powdered materials together by distributing a fine layer of powder on a surface which is then fused in the desired pattern using a laser. The platform is then lowered by one layer and the height difference is filled with more powder which is then fused to the existing solid layer. This process is repeated and when the object is created the excess powder is brushed off and can be reused for a new object. One example of this technique is “direct metal laser sintering” which uses metal powder resulting in dense objects with mechanical properties similar to those of a cast or machined component. Similar techniques are “selective heat sintering” where a heated print head melts powdered plastic successively layer-by-layer. A third variant of sintering is “electron beam melting” (EBM), a specialized technique using electrons to fuse metal powder. This is a process that is conducted in vacuum in temperatures of between 700°C and 1000°C making a suitable technology for creating objects of reactive materials such as titanium (Bogue, 2013). The process of Sintering is visualized in Figure 10 below.

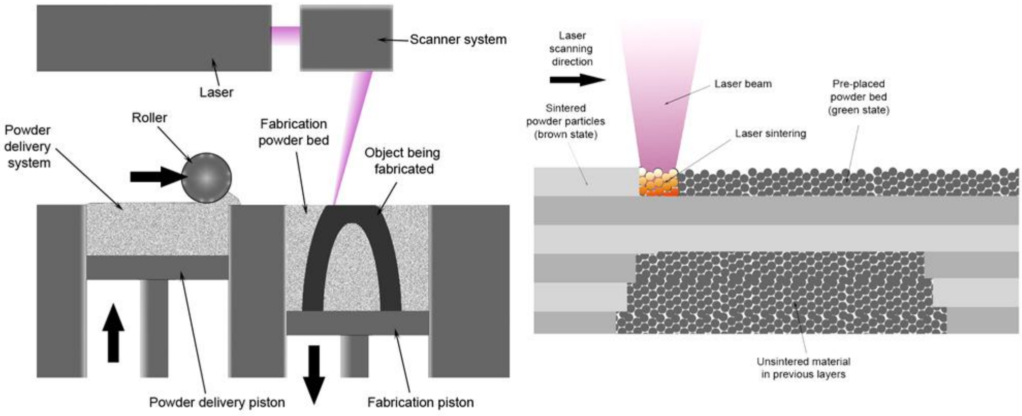

Figure 10, Visualization of the Sintering technology, which uses a powder bed. (Source: Wikipedia, 2015b)

Basiliere (2014) states that there are seven different 3DP technologies. These seven are listed in table 6 below. This table also provides the wide range in price between various printers. Six of these can group into the three previously presented technologies; FDM, Stereolithography and Sintering.

	Technology	**Price Range**
FDM	Material Extrusion	$500 to $400,000
Stereolithography	Stereolithography	$3,000 to $800,000
	Material Jetting	$20,000 to $600,000
Sintering	Binder Jetting	$5,000 to $1,800,000
	Directed Energy Fusion	$200,000 to $5,000,000
	Powder Bed Fusion	$19,800 to $2,000,000
Other	Sheet Lamination	$37,000 to More Than $1,000,000

Table 6, 3DP technologies, prices in USD. (Source: Basiliere, 2014)

Material Extrusion is the same technology as FDM but since the latter is a trademark, most 3DP manufacturers call their specific version something else. Material Jetting uses a liquid resin and is thus a stereolithography technology. Binder Jetting, Directed Energy Fusion and Powder Bed Fusion are all using power beds that are cured layer-by-layer, i.e. sintering technology. Sheet laminating is the process of bonding thin sheets of material (typically paper or metals) together using adhesives. This technology is a 3DP technology but cannot be grouped to any of the three mentioned technologies (Basiliere, 2014).

Until today, most printers use various kinds of plastics as building materials. However using sintering, objects made out of metal are possible, as well as titanium. Various kinds of ceramics are possible to manufacture with any of the three technologies (Lipson and Kurman, 2013).

Benefits of using 3D printing

3DP is characterized by a number of beneficial traits that differentiates the technology from traditional manufacturing techniques such as milling and casting. The identified benefits are listed below and then each presented in this section.

- Complex geometrics.
- 3DP simplify and reduces the number of actions need to create an object.
- Flexibility.
- Mass customization.
- Low unit cost while having a high degree of customization.
- Decentralized production.
- Availability of designs and CAD files online.
- Less material usage.

3DP enables the realization of designs that may not be possible with other manufacturing methods (Campbell et al. 2011; Mellor et al. 2014). With the help of 3DP one can create an object without any need of final assembly, welding, or attachments. This can be illustrated with the help of a chain, a product containing a series of interconnected rings that have all been welded together. With the help of 3DP, welding is not needed since the rings are printed already encircled by each other. Thus, 3DP simplifies and reduce the number of actions needed to create a final object.

In addition to this, there is an opportunity to make designs that are not possible to create at all using traditional manufacturing methods. 3DP enables objects with a very high degree of complex geometry. A team led by Arup, an engineering firm within the construction industry, has created a steel joint with a very high geometrical complexity. This level of complexity is not economically viable with any other production method than 3DP. Below are two pictures, one shows the 3DP component and one shows the welded together component (Pitcher 2014). The durability and strength of this steel joint is not explained.

Figure 11, Arup 3DP Steel Joint (Source: Pitcher, 2014)

Figure 12, Steel Joint which is welded together (Source: Pitcher, 2014)

In line with the design freedom and the possibilities of complex geometries, 3DP enables high flexibility and uniqueness. This is the case since 3DP provides the possibility of making each object unique by simply adjusting the design for each print in the computer. This requires less time and resources than to change for example a cast for each moulding of an object. If one wants to make unique objects using casting, each cast needs to be made unique which is far more resource demanding than to adjust parameters in a CAD file on the computer. Thus casting works great for products with a high degree of standardization while 3DP is appropriate when there is a high degree of uniqueness and need for flexibility (Beaman 2013).

Hence, 3DP enables economy of one and the ability for highly customizable products (Petrick and Simpson 2013). Economy of one stands in contrast to economy of scale, a concept that regards low unit cost for mass production. 3DP is not suitable for interchangeable standardized part produced at high volumes. For those parts traditional production methods are more appropriate.

However, when products needs customization, the unit cost becomes higher with traditional manufacturing, an issue 3DP by nature does not adhere to. Basiliere et al. (2014) speaks of mass customization, the ability to provide a large quantity of unique components. With 3DP the unit cost is basically constant regardless how much variation to the component you make (Beaman 2013). This is illustrated in Figure 13 below.

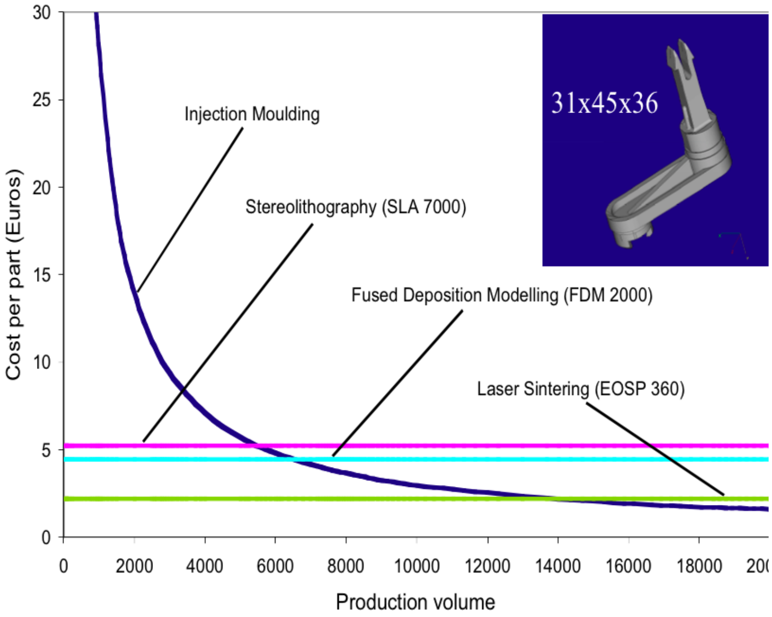

Figure 13, Unit cost for various production methods. (Source: Beaman 2013)

The supply chain can be changed when introducing 3DP. 3DP facilitates flexibility not only regarding geometry, but also regarding the geographical location of the production. With 3DP, production is decentralized and can be put closer to the end user. Instead of creating one large factory and then send the products to the customers, the production can be made by 3D printers situated where the components are needed. The benefits are shorter lead times and less inventory since components can be produced when they are needed (Petrick and Simpson 2013).

Bogue (2013:311) speaks of a “new type of industrial revolution” and Campbell et al. (2011: 1) speaks of a “revolutionary emerging technology”. Burkett et al. (2014:6) is more hesitant stating that “3DP is slowly emerging to disrupt select manufacturing processes and supply chains”. Barack Obama stated that “3DP has the potential to revolutionize the way we make almost anything” (CNN, 2013). What is believed to be truly revolutionary is that the flexibility and complex geometrics of the printed objects can lead to a changed production system (Bogue, 2013; Campbell et al., 2011; Burkett et al., 2014). An example can be that instead of choosing between dolls on toy store’s shelf, one can design and print customized product at the store. Furthermore, in May 2013, 100 000 persons were quick enough to download the files for a plastic handgun before it was forced off internet by the US Department of Homeland Security. This was all that was needed to create a fully functional and printable firearm by a 3D printer bought on eBay for 800$ (Bogue, 2013).

Finally, 3DP uses less material than traditional manufacturing techniques. One example is from the aerospace industry where it is claimed that 90 percent of the material needed for a specific titanium part can be saved, using 3DP techniques, compared to using conventional manufacturing methods (Mellor et al., 2014).

Separating the usage today and the potential usage of tomorrow

In the above section, benefits of 3DP were described. In this section the limitations and drawback of the technology is presented. This will add to a complete and realistic point of view of the potential of the technique.

The major drawbacks of 3DP are the following issues:

- Availability of materials
- Quality
- Detailness
- Size
- Speed
- Costs

Today's commercial 3D printers can print in plastic, ceramics, and metal. There are also some experiments using biological materials such as wood or tissue. However, the majority of the printed objects are done with plastics. More advanced printers can use metals but the objects are then limited in size, speed and quality plus the fact that those machines are expensive. What can be achieved on a desktop 3DP is not the same as what can be achieved on an industrial machine. This distinction between the two is somewhat blurred in the media attention between the two (Vinnova, 2014).

One of the reasons 3DP is not yet commonly used as an end manufacturing process is because the strength and end-quality is not as good as using a traditional manufacturing process. Tyrrell (2014) states that a 3DP object may look good on the outside, but as of now, it cannot be assured that it behaves the same under load pressure as traditionally manufactured parts. And even if the 3D printed parts or components are as good as a traditionally manufactured part, there are not as many certification and quality assurances for traditional manufacturing process that 3DP does not have (Kristiansson, 2014).

In addition, 3DP is a slow process. The speed depends primarily on the size of the object, the level of detail, the type of technology used, and what type of machine is being used. Some parts may take hundreds of hours to print (Tyrrell, 2014).

The final limitation is the size of the object. A 3DP cannot print anything larger than itself. A consumer based machine such as MakerBot Replicator can print object up to 28.4 x 15.5 x 15.2 cm (MakerBot, 2015). A 3DP service provider, Sculpteo can print slightly larger, having 67 x 36 x 56 cm as a maximum size. And even though larger objects are desirable, the printing time and cost of material increase with a power of 3 when the size is increased. A plastic cube measuring 3x3x3 cm need 27 cm^3 material. A twice as large object demands 6x6x6 = 216 cm^3 in time and material. Doubling the size leads to 8 times longer production time and use of material.

Finally there is a setup cost to factor in. Even though 3DP uses much less material than subtractive processes such as milling, the initial materials outlay for a 3DP can still be high. According to Tyrrell (2014), filing an industrial laser sintering machine with virgin titanium powder can cost thousands of pounds.

Areas of application for 3DP

There are two main usage areas for 3D printing (Bogue, 2013):

- Making end products or components
- Making prototypes

What differentiates these two types of objects is that prototypes is not used as an end product but rather is a step in towards making a finalized version using another manufacturing technique. Prototypes can be used as way of find the right design for something that will later on be used either via a more advanced 3DP manufacturing technique or a tradition manufacturing technique (Lipson and Kurman, 2013).

In Figure 14 below, data provided by Jannek (2013) is used to visualize the percentage of sales from different sectors. Example of usage within each sectors are hearing aid within the dental industry, lightweight components for the aerospace industry and prototype usage for the automotive industry (Vinnova, 2014; Buswell et al., 2006; Levy et al., 2003). Berman (2012) list dental crowns and artificial limbs as promising application areas. Utilization of these methods within the construction industry is however limited but "is set to increase" (Buswell et a., 2006:224).

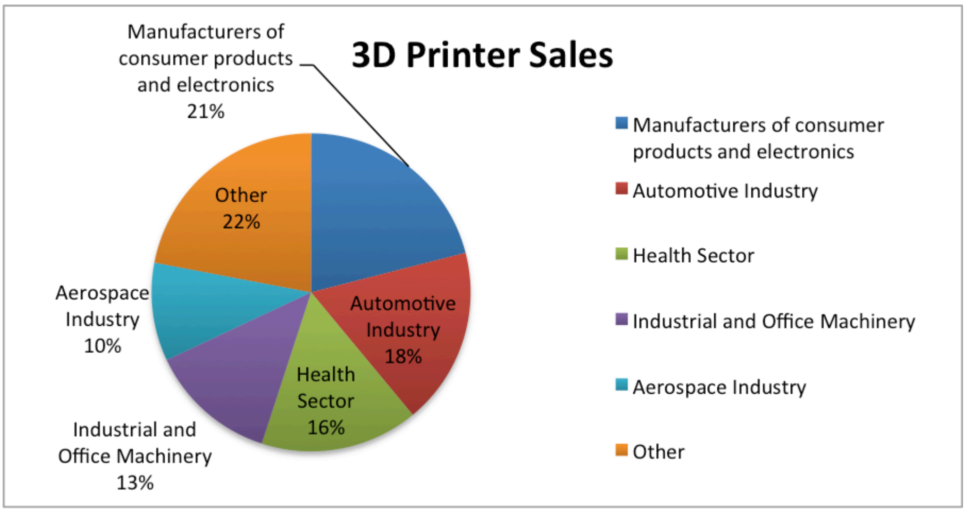

Figure 14, Proportions of sales from different sectors (Source: data used from Jannek, 2013)

Lim et al. (2011) presents three different large scale concrete manufacturing technologies, Starr (2015) presents printing of entire houses. These printing technologies are basically a concrete extrusion robot that can move in three dimensions and thus create an object. These concrete objects are created without the use of a cast (which is the traditional way of using concrete), and they have a high degree of design flexibility, and with reduced involvement of labour. However, the objects suffer from lack of durability due to lack of rebars. It is emphasized by Lim et al. (2011) that this is an emerging technology that cannot be used as of now.

According to 3DP specialist: Empirical evidence of the technological readiness of 3DP.

In addition to the review of literature regarding 3DP presented above, empirical findings regarding 3DP has also been gathered by interviewing 3DP specialist at Swerea IVF in Mölndal, Sweden. Swerea IVF is a research institute that works in close collaboration with primarily manufacturing industry and textile industry (Swerea, 2015). One of their research areas are within 3D printing. Swerea is an organization that have had collaborations with NCC other business areas, however not any on 3DP. By interviewing a 3DP specialist, a comparison can be made between the literature regarding 3DP and the opinions of a field expert at Swerea.

At Swerea IVF they have two types of 3D printers; one called MakerBot replicator 2 and one Formlabs Form 1+. The MakerBot uses FDM technology and prints using a filament based on polymer. Noteworthy is that it has two printer heads which enables the creation of two coloured objects. The formlabs machine uses stereolithography and it uses a liquid resin which is a type of polymer as well.

When asked about potential usage areas, the 3DP specialist at Swerea says that 3DP usage can divided into two main groups; end components and prototypes. What differentiates these two types of objects is that prototypes is not used as an end product but rather is a step in towards making a finalized version using another manufacturing technique. 3DP is primarily used for printing prototypes as of now. These prototypes can be used for various purposes, such as visualization, testing and proof-of-concept in product development.

As a demonstration of 3DP's potential, a two examples or 3D printed objects were discussed. The first is a 3D printed wrench. It is printed in one piece, without any need of final assembly but still has an adjustable spanner, just like an original metal wrench. This object shows two main benefits of 3DP; the prototypes are functional, i.e. having a moveable spanner, and that they are made in one piece, without any need of final assembly. By printing a functional prototype with a 3D printer, the design, functionality and the can be verified and be put under feedback. Therefore 3DP is a useful tool in product development.

Another prototype was used for testing if a specific shape and form could be created in a CNC machine. This CNC-machine had multiple cutters which could be verified to be able to create a certain shape by first printing the shape using a 3DP prototype. This physical 3DP prototype could than visually be used to test if the different cutters in the CNC-machine could reach all holes, or if the various angles were possible to create. Thus this prototype had a specific purpose of testing it "manufacturability", but for most prototypes its purpose is to get a "feel" for the shape and design - a much more general benefit. Printing an object adds the ability to hold and see the object compared to viewing a 3D model in the computer.

Apart from prototyping, 3DP end components are used when there is a need for small and highly customized items. One such area is making dental implants, where each unit needs to be unique, and they are small enough to be 3D printed. For example, a 3DP specialist mentions the Swedish 3D printer manufacturer Arcam, whose machines creates hip implants. Yet again these objects meet the constraints of 3DP. These objects need to have a unique shape, and a size enough small to able to be printed using 3DP. To give some indication of the time to print, Arcam is able to print 100 implants in 80 hours. Generally, the time to produce an object is primarily dependent on the level of detail you need.

There is an opportunity to create objects with very fine detail using plastics, ceramics and metals. Since the technique adds layer-by-layer, there will be some edges on the surface. The size of these edges, i.e. the smoothness of the surface, depends on the level of detail you have chosen. If you choose high detail, each layer becomes thin and more layers are needed to create the object of the same size compared to if you chose a lower detail level. The drawback of choosing a high detail level, i.e. using many layers, is that the object takes longer time to print. The time needed is proportional to the number of layers.

Most of the potential benefits of 3DP, such as lowered cost for small batches (Petrick and Simpson 2013), flexibility (Campbell et al., 2011), economics of one (ibid.), complex geometries (Pitcher 2014) and the ability to create functional prototypes were all confirmed by a 3DP specialist. A 3DP specialist also adds to the writing of Tyrrell (2014) that there is a lot of hype regarding 3DP. The specialist stresses that 3DP should only be used if there is a clear benefit of using it; one should not only start using it just because it is a new technology. Finding the clear benefit is therefore crucial.

NCC - a project based organization that constructs products with high demands for durability

In this section of the empirical findings, a brief overview of the construction industry in general and NCC in particular is presented. At the end, the reader is introduced to a few areas of application.

The construction industry is highly regulated and the demands for durability are in some cases extreme. The products that NCC produces are not an exception from this. For example, NCC must prove that its bridges will last for 120 years. In addition, the size of the products (e.g. bridges) and even components (e.g. beams) are generally large and made out of concrete, asphalt or steel.

The organizational structure of NCC follows the how the rest of the industry is organized. Construction companies are generally highly decentralized, where most of the workers are working with separate projects with few connections to workers in other projects. As a consequence, the location of innovation is also decentralized, where much of the innovative efforts are done by individuals on single projects. In addition, NCC outsources a substantial part of the man-hours in projects, which further complicates organizational structure. Also, since large parts of the organization is project based, it is hard for top management to govern and change operations within the projects, e.g. to introduce a new technology. Although evidence from interviews indicates that development work between projects at NCC is centred around operations development and the usage of information systems. Some joint efforts with subcontractors of improving specific products, such as improved windows that do not reflect telecommunication signals, are also being made between projects.

Construction projects are always initiated by clients' requests and projects at NCC is not an exception. The customers in construction projects do not only initiate the projects but are also involved in the decision making during the whole process (Jensen, 2010). Being able to communicate design ideas, problems and problem resolution through the interface with the customer is therefore crucial for each project to succeed according to plan, which NCC confirms. Compared to the manufacturing industry, where the producer is able to develop the product before the customer order, the construction industry has a harder time optimizing its value chain (Produktionbygg, 2014).

An initial round of interviews provided several possible areas of application for 3DP. The areas of application were both end-components and using 3DP for prototyping. In total, three areas of application were defined:

1. 3DP end-beam structures in bridges

3DP end-beams could move or rationalize the welding of the components at the end of beams, which would decrease the size of the beams. Avoiding welding in parts which are part of the load-bearing structure is desirable, because welding creates microscopic tensions in the steel that weakens the beam. Smaller beams would lead to less material used, and thus, cost savings could be made. The beams are one of the main cost drivers for bridges.

2. 3DP Pole-shoes

Pole shoes are placed on the bottom of poles, which makes it easier to penetrate the ground. The pole shoes are made out of massive steel, and NCC alone uses thousands of poles in Sweden each year. Using a beam structure, where beams are placed in a geometrical complex pattern. The beams could be placed only on places only where the pole shoe is exposed to forces when penetrating the ground.

3. Using 3DP for prototyping

NCC extensively uses virtual prototypes and models throughout all parts of a project, but physical prototypes are not systematically being used. An initial discussion with a senior person within the R&D unit at NCC confirmed that benefits of using physical prototypes are recognized but not implemented. Prototypes could be used during several phases of a project, with different purposes. The step to also use physical 3DP prototypes is small because data from virtual prototypes can be used to use a 3DP to print prototypes.

4.1.3 Analysis of Cycle 1 - Exploring the technological development of 3DP

In order to analyse the empirical data presented in cycle one, the literature concerning technological development is used. To be more precise, to evaluate the development up today the TRL-framework is used, and then concepts derived from the TLC is complement to a broader assessment of the technology as of today. All in all, an attempt to place the 3DP technology on the technology S-curve is performed with the basis of all preceding analyses. Also, an outlook into the future developments, using the TRIZ laws is presented. The aim of the said part of the analysis is to answer the first research question:

1. What is the readiness of the 3DP technology in the two main areas of application (End-components and Prototypes)?

In addition, a discussion about the specific requirements and regulations that the construction industry in general and NCC in particular must comply with when talking about new types of components and technology. The specific discussion aims to answer the second study question of this cycle.

TRL – A cross-sectional analysis of the development of the technology up to date

As presented in the literature section, the basis of the TRL-framework is the 1-9 scale, where the first step is basic university research and the last fully commercialized technology. This analysis will entangle where on that scale 3DP is today. One can assess the level of readiness for 3DP from various points of views; TRL of a specific industry, TRL for a specific application area, and TRL for a specific material.

First, when looking at the technical capabilities of 3DP, Tyrrell (2014) provided limits in terms of size, speed and initial setup cost. A 3D printer cannot print an object larger than itself and this limiting the application areas for using 3DP for end components. The speed of 3DP is not very fast either. 3DP is useful when manufacturing unique objects but if you wish to create identical copies, traditional manufacturing methods are both faster and cheaper. 3DP is not suitable for economy of scale which is the purpose of most manufacturing methods. Instead 3DP adheres to the economy of one, the ability to create unique objects. Furthermore, the initial setup cost is high, industrial machines can be very expensive. This is however not always the case since there is a large difference in product range, as shown in table five.

The present application areas of 3DP for manufacturing end-components is today in industries that differs vastly from the construction industry. The identified areas of application today are; dental implants, hip implants, and hearing aids. These application areas of these industries differ from those of the construction industry since the former demand small objects and their material can be of plastic, polymer or ceramics. Porous materials such as ceramics are good for implants, and plastics are considered preferable for hearing aids. Due to this the readiness of the technology is arguably high for making implants, but low for making end components in other sectors.

There are also experiments of using 3DP at sea or even in space (Snyder et al, 2013). Providing the space station (or even a ship) with supplies is difficult. Therefore a 3D printer may be able to print spare parts on site, which is convenient since it shortens the lead times significantly. Thus, 3DP is considered useful for hard to reach places, or where the supply chain is complex. However, these issues cannot be attributed the construction industry in general, nor NCC in particular.

As presented in the literature, TRL lack a critical point of view, why a discussion concerning pro-innoation bias is presented. In Sveiby's et al. (2009) article "unintended and Undiserable Consequences of Innovation" a review of innovation literature showed that 0.2 percent of publications discussed the undesirable effects. This bias towards only showing the positive traits is arguably the same as in the articles presenting futuristic 3DP concepts. As found in the empirical data, few limits to the innovations such as rigidity, durability or quality is presented, instead it is only the positive traits that are presented, which is in line with the concept of Pro-innovation bias. These futuristic concepts of 3DP are interesting, but it is arguably wise to study 3DP more and follow the development more thoroughly before investing.

When assessing the readiness level of 3DP for various industries the difference is large. For medical implant usage, the readiness is arguably higher than in the construction industry. There is implementation of 3DP for making implants or hearing aid, which points at a high TRL level - arguably up to a level of 8 or 9. For the aerospace industry, which is interested in the ability to create light weight components, the readiness is lower since the number of application areas are still few, leading to position in the middle of the scale. There are few, if any, examples of fully commercialized printers or printed objects used in the construction industry. Thus, it can be stated that the readiness for end-components within the construction industry is low.

Moreover, TRL can be analysed with a perspective of the two major types of material being used; metal and plastics. Since 3DP was originally created for plastic usage, this is where the development have come the furthest. There are a multitude of available machines, and the market is increasing rapidly especially for consumer based 3D printer. The maturity for 3DP of plastics is therefore high, at a level of 8 to 9. Looking at 3DP of metal, which is used for manufacturing end-components, the readiness is not as high. What can be achieved on a cheap desktop 3DP (using plastics) is not the same as what can be achieved on an industrial machine. The recent media hype around 3DP has tended to blur the distinction between the two. There are some actors with the ability to create metal prints, e.g. Arcam, which prints in Titanium. But these fewer actors creating theses type of printers and both the fixed price of setting up a machine as well as the cost of running is high. The readiness of printing metal end-components is therefore much lower than plastics.

All in all, applying the frame work of TRL presented by Mankins (1995), it is hard to specifically pinpoint on which level 3DP is but above stated arguments indicates that the technology are somewhere in the middle on the scale. Generally, 3DP for end-components has left the research labs of the universities but is not yet fully commercialized. By drawing on the TRL-analysis of materials, one finds that the readiness is higher for plastics, which is almost exclusively used when prototyping, the readiness for prototyping is clearly higher.

Analysing 3DP with the concepts derived from TLC

The main concepts derived TLC is the concept of Era of ferment and dominant design. It is argued that, with the empirical daa as evidence, there are clear indications that 3DP is in an era of ferment and that no clear dominant design has yet emerged.

By applying the concept of technology life cycle provided by Nelson and Winter (2002) on the 3DP market in general (and not on the construction industry), one finds that 3DP is arguably relatively early in its lifecycle. Since the expiration of some key patents, the number of manufacturers has increased immensely, making is hard to identify key players on the 3DP market. There are also a multiple numbers of techniques such as sintering, lithography and FDM. Within each of these technologies, there is also a wide range of types of printers depending on if they are for consumer usage or industrial usage. The number of types of 3DP technologies and actors on the market indicates that 3DP is in an era of ferment, which is the phase where many different technologies and actors are present on the market and no dominant design has yet been settled. An absence of a dominant design means that that technology providers focus on developing new products and concepts, rather than developing and further improving one or a few selected technologies. For NCC, this means that there is a great risk if they want to implement one of the many technologies, since the technology chosen may become obsolete if another technology becomes the dominant design.

When looking at the construction industry in particular, future application areas such as printing entire houses (Starr, 2015), concrete extrusion robots (Lim et al., 2015) are exciting but since tose are only 3DP prototypes they still needs to pass some strong thresholds. There are opportunities to automate construction but what is "printed" is not close to being a finished building. There are no rebars, insulation, electricity, VA-system or even windows. Furthermore the rigidity and durability of these buildings are still unknown (but assumed to be low since they lack rebars). Since no explanation of the durability of any of these concepts are explained or accounted for, this is considered to be not on par with traditional manufacturing methods. Thus, due to the fact there are many different 3DP prototypes that the market is not even close to present candidates for a dominant design, 3DP for end-components in particular is at the early stages of the era of ferment.

The implications for NCC of this is that if NCC e.g. would start a joint development on a specific 3DP technology, the efforts could possibly become obsolete since the risks of choosing a technology that does not become the dominant design are high. Since the market cannot even present candidates for a dominant design, the risks are arguably high.

Putting the 3DP technology on the technology S-Curve

With the basis of the preceding analyses an attempt to put the 3DP technology on the technology S-curve is made in this section.

By starting looking at the output from the TRL analysis, one finds that the readiness for end-components is rather low while it is higher for prototypes mainly due to the specific material readiness of plastics. Moving over to the concepts of era of ferment and dominant design, the 3DP technology applied in the construction industry context shows in particular low level of development due to the clear state of era of ferment and lack of candidates for dominant designs. In addition, when looking at the Garner group's hype cycle, further indications of 3DP's limits is found. It shows that most application areas are two to five or even up to ten years from maturity (Basiliere and Shanler, 2014). Preceding argument is also strengthened by a 3DP specialist at Swerea IVF who stated that the readiness of the technology to use it for printing of end components is low (with some exceptions) but rather high for prototyping. An S-Curve could enfold as follow:

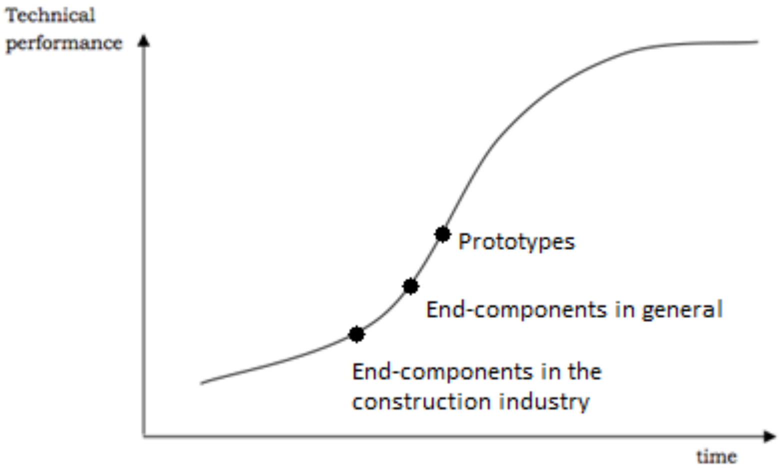

Figure 15, An attempt to put 3DP on an S-Curve (Source: Lindmark, 2006)

When looking at the rate of technological development over time, one can argue that the development of 3DP has been slow for many years. The technology was introduced to the market in the early 80's and it is not until a couple of years ago the sales have picked up. By the entrance of many firms, the technological innovations are probably happening faster as well. Arguably this puts 3DP in general on the beginning of the steep part of an S-curve since the development seems to have picked up its pace. However, there is a need for a large data set and a study outside the scope of this thesis to measure the absolute technology development of 3DP. Since there are many manufacturers and even more models available along with multiple technologies currently on the market, measuring the performance development for 3DP in general is difficult. In addition, there are many traits of 3DP that are of importance when assessing the development of a technology. As found in the empirical section of this cycle, speed, level of detail, cost, availability of materials, and durability are all important factors. An S-curve of speed would probably look different from an S-curve of durability.

When further analysing 3DP prototypes and the corresponding state of development, one can assume that it is dependent on the development of surrounding technologies. First and foremost, to print a prototype, data of the prototype must exist, and second the data must be converted to 3D-printing friendly format. Since NCC already uses virtual prototypes that contains large amount of data, the prerequisites for using 3DP prototypes exists. Applying the logic of Lindmark's (2006) theory about the development of sub-technologies in the context of NCC, the potential usage of 3DP prototypes at NCC is dependent on the development on software that can convert the data in order to print prototypes.

Future outlooks using the nine TRIZ- laws

Up to this point, the current state of development of 3DP has been made by using the TRL-framework. The analysis was complemented by using concepts from the TLC, and all in all the analyses was used to put the 3DP technology on the technology S-Curve. Although, it reasonable to assume that 3DP will be futher developed in the future, and a possible framework to use in order to predict the said development is the nine TRIZ-laws.

TRIZ-laws	End-components	End-components in the construction industry	Prototypes
1. Law of increasing degree of ideality	Getting increased output to the same cost or the same output to a lower cost.	It is found that critical development in durability and quality needs to be done in order for 3DP to be fully implemented. Thus, the market forces will most likely push developers to improve durablity and quality .	Higher printing speed to the same or cheaper cost.
2. Law of non-uniform evolution of subsystems	Different rate of increase in materials and printing speed.	Increased development of materials in order to get improved durability and quality.	Increased user-interface, such as software where prototypes are constructed or improved convertability from existing virtual models.
3. Law of transition to a higher-level system	More types of materials and colors that can be added to the components	Inclusion of rebars and other construction-critical elements in end-components	Prototypes with several different colors. Today this is done by adding more printer-heads.
4. Law of increasing dynamism	Today on flexibility limit is that 3DP cannot create objects larger than the size of the machine. A printer that is able to print objects larger than itself will radically increase the flexibility of potential objects.	Printers that can be placed in the harsh environment of construction sites, leaving the printer labs.	N/A
5. Law of transition to micro-level	Using smart materials with e.g. nano-technology. Inclusion of circuits in components.	Using smart materials with e.g. nano-technology. Inclusion of circuits in components.	Using smart materials with e.g. nano-technology. Inclusion of circuits in components.
6. Law of completeness	A self-diagnostic printer that inspects the object being produced and can adjust the file or even repair while being produced.	Same argument as for end-components in general.	Same argument as for end-components in general.
7. Law of shortening of energy flow path	Some of the technologies, such as Electron Beam Melting, used by Arcam requires temperatures up to a 1000°C. A shortening of energy flow path is arguable a	Same argument as for end-components in general.	Shortening of distance to virtual models. in other words, more effective convertion

	reduction in the needed heat. An automatic conversion from any type of virtual model to a 3DP ready file would also shorten the effort needed to use 3DP.		of data generated from virtual models.
8. Law of increasing controllability	Assuming that the second law will be enforced, materials and the virtual models may develop at different speed, which can lead to very complex models while the development of materials is not keeping up to support the development of more complex models. A printer that can align the two could be a possible development.	Same argument as for end-components in general.	Same argument as for end-components in general.
9. Law of harmonization of rhythms	N/A	N/A	N/A

Table 7, TRIZ-law and the development of 3DP

In summary, the development for end-components in genera has passed some critical thresholds in terms of quality and durability, but in order for 3DP to reap market shares from conventional manufacturing the printing process must become more effective. In other words, the output from 3DP must increase without an increase in cost or produce the same output to a lower cost. For end-components in the construction industry, some critical thresholds must be passed in order for the market to embrace the technology. Also, a transition to a higher-level system in order to include rebars is of critical importance for end-components in the construction industry. For prototypes, the speed is assumed to be of importance, since the theory presented by Liou (2008) states that the biggest advantage of 3DP prototypes is the ability to frequently and iteratively print prototypes.

External factors – Regulations and certification in the construction industry

When turning the focus towards the demands for certification and durability for components that NCC sell there is a mismatch between components printed by 3DP. This was emphasized by a senior person within the R&D unit at NCC who stated that the objects are large and are subject to immense regulation and quality assurance. Certification is a useful tool to add credibility, by demonstrating that your product or service meets the expectations of the customers. So far, the empirical evidence shows that this is not available for 3DP products of components. In short, the construction industry has high demands for durability, size, and certifications, which stands in sharp contrast to the present possibilities of 3DP.

Some potential end-component application areas were found during the initial interviews; pole-shoes and end-beams structures were identified. Pole-shoes would primarily make use of the complex geometry of 3DP components which would limit the amount of material needed. The end-beams would make use of the possibility of creating a product in one piece, which would eliminate the need for welding. Unfortunately, both of these potential end-component components are possible to manufacture using 3DP today. Arguably these examples are well representative for the end-component need within NCC Construction. There might be more suitable applications areas found by running more brainstorming sessions or similar, but probably these will fail to meet the limits and constraints of 3DP as well.

Therefore, application areas for making end components at NCC are concluded to be useful areas in the future, but not today. A research project concerning the use of end-components would rely on future technical advancements and hypothetical speculations about regulatory changes. The researchers of this study recognize that it could be possible to use such 3DP end-components for commercial use in the long term future, but such research work would be of little practical use for this time being.

A combination of extensive knowledge about of virtual prototypes within NCC and the inherent absence of regulation on prototypes, the step to using physical 3DP prototype is small. Also, according to industry reports, prototyping in general is the main area of application of 3DP as of today.

4.1.4 Refined Hypothesis of Cycle 1

- The 3DP technology has enough readiness to be used to print prototypes (validated)

4.2 Cycle 2 – Problems in the early phases of projects and how 3DP prototypes may address these

4.2.1 Hypotheses

- There is a potential area of application of 3DP prototypes at NCC (to be tested)

4.2.2 Study questions

- What are the main problems in the early phases of projects that NCC issues and where are there room for improvements?
- Comparing with virtual prototypes and models, what are the main advantages of 3DP prototypes?

4.2.3 Empirical findings

To answer the study questions, data about the current usage of prototypes (which is exclusively virtual prototypes) was collected. A section describing the product development process at NCC is presented because conventional theory about prototyping is often concentrated on the use of prototypes in the product development process. Also, the answers to some of the questions can be found in the literature about prototypes, which is interwoven in the analysis.

Prototype usage at NCC

NCC uses different types of prototypes during different parts of a project, although nearly exclusively virtual prototypes. Efforts on creating physical prototypes are usually initiated by architects, and most often created for houses and other properties. For all larger projects, virtual 3D-models are being used, while for the smaller projects only 2D blueprints are used.

Building Information Modelling (BIM) is a tool that is used in the construction industry, and NCC is one of the Nordic leaders in developing and using it. BIM is defined as model plus information, meaning that a model always contains information such as length of beams or volumes of needed concrete. The tool is mainly a support decision program when several pieces of information need to be put together. NCC has a vision that everybody on a project should use the BIM model, making it the centre of information exchange. The information exchange extends not only to the internal planning phase of projects, but also to when communicating the tendering offer and when starting up the project with the client. The development is emphasised as an important area of improvement to further developed NCC's position within the construction industry.

Although, some drawbacks with the increased use of virtual prototypes and models were found. One is that some people and sometimes even whole divisions at NCC do not fully utilize all the advantages of virtual prototypes and models. A simple explanation to this is that many of the employees at NCC have many years of experience of doing things they always have been done. Another explanation is that NCC is highly decentralized where each geographic division is responsible of implementing such technologies. Some of the divisions are rather small and employing the resources needed is therefore comparatively large investment.

Development work at NCC

The infrastructure section alone at NCC completes more than 1000 projects each year (NCC, 2015). These vary in size, type, contract form and in many other aspects, which makes it hard to paint an overall picture of an infrastructure project. Presenting the development work within and between projects is even harder, partly due to the complex project based organisation. What is clear is that NCC works with three different types of development; product development, project development and project adjustments.

	Within projects	Between projects
Product development	X	X
Project development	X	X
Project adjustment	X	

Table 8, Development Work Between and Within Projects

As the table shows, both product and project development are performed within and between projects. Since NCC is highly project based, much of the resources are tied to projects whereby much of all types of development are performed within projects. Due to this decentralized organisation and incentive structure, NCC does not have a "conventional" R&D unit similar to the ones in the manufacturing industry. Concerning the product development, the development of product can either stem from an identified problem within a project whereas a solution to that problem is developed. If the solution is highly project specific, a new innovation (either a product or project development) is not incorporated in the organization after the project is completed, but if there is a possibility of reaping monetary benefits by using the same solution in future projects, the innovation is extracted and internalized in future projects. On the other hand, product development on products that for certain will be used in future projects and can be subject to economics of scale, such as new types of windows, development can be performed between projects. The same logic goes for project development, which could be the way of using decision support system and BIM-models.

Project adjustment is the process in which products and procedures developed in past projects (or between projects) are adjusted to a specific project. This could be extending the length of a certain beam, or the process of managing subcontractors. Due to the nature of this work, project adjustment work is only conducted within projects and mainly within the projection phase.

A paradox when talking about development within versus between projects is that monetary resources are tied to specific projects, while at the same time there is often tight deadlines and little time for development. Resources in terms of time on the other hand exist between projects.

4.2.4 Analysis of Cycle 2

The focus of this report is to identify problems within NCC which will indicate areas of applications for 3DP. The empirical findings in Cycle 2 contribute to this by analyzing the findings of development work and prototype usage, with the theory of Verganti (1999). The following analysis will aim to answer the first study question:

- What are the main problems in the early phases of projects that NCC issues and where are there room for improvements?

Looking at development work, it was found that NCC is primarily project-based, where the development work consists of product development, project development and project adjustment. In addition, the present usage of prototype was presented which primarily consist of virtual models. These virtual models are different from physical prototypes, which can be manufactured using 3DP. These two factors - present development work as of today, and use of virtual models – are of interest when analyzing Verganti's (1999) view on anticipating capabilities during the early phases of a project.

In any project or product development process, there is a trade-off between the uncertainty of what changes to make and the cost of making a change to a product. This means, as the time progresses the amount of information and insights about the customers' needs increases, although the cost of making changes increases exponentially (Gedhardt, 2003). According to Verganti (1999) high performing product development projects have two key factors; anticipation and reaction capabilities. The anticipation capabilities are the projects team's capabilities to anticipate information in the early phases of a project. Anticipation of information reduces the uncertainty at the early phases of a project.

Verganti (1999) argues that for that the difference between high and low performing product development projects is due to two key factors; anticipation and reaction capabilities.

- Anticipation skills: the capability of anticipate information in the early phases of a project.
- Reactive skills: the capability of effectively introduce changes in the later phases of a project.

When more closely analysing, anticipation skills, Verganti (1999) argues that this capability is dependent on three variables:

1. Systematic learning (the mechanisms and ability to learn from past projects)
2. Teamwork and communication (the early involvement of all major actors having a direct contact with future constraints further on during the project)
3. Supported proactive thinking (the use in the early phases of different checklist, failure and effect analysis and early prototyping)

The first item of that list, systematic learning is an aspect of anticipating capabilities that is found to be dependent on the organizational structure of a firm. In the Case of NCC, the empirical findings tells that systematic learning is arguably achieved sufficiently by NCC. NCC performs over 1000 projects each year, and they conduct product development and project development both within projects and in between. This is illustrated in Table 9. That there is activity performed in between projects and not just in projects, is a mechanism that enables NCC to learn from past projects.

However, the second item of anticipation skills, teamwork and communication, is arguably a trait that is related to the use of prototypes. The fact that NCC primarily use of virtual and very limited use of physical prototypes is arguably an issue to the communicational capabilities Verganti (1999) argues that the communicative aspects are important. This is the case because, as the time progresses, the amount of information and insights about the customers' wants increases, although the cost of making changes increases exponentially. The ability to early on take decisions is an inherently difficult problem due to the lack of information. The ability to get a hold of as much information for all the project members is arguably dependent on the quality of the communication. And the quality of communication is found to differ between virtual and physical prototypes.

The researchers of this study argue that NCC work with virtual prototypes can be grouped into the Focused Analytical category, provided by Liou (2008) (Table 7). Analytical prototypes are used when the product or element is to be tested, virtually simulated and analytically analysed. Focused prototypes only display one or a few variables, which we have found is the case for most the 3D tools used at NCC.

	Learning	Communication	Integration
Focused analytical	X		
Focused physical	X	X	
Comprehensive physical	X	X	X

Table 9, Roles of Prototypes vs. Types of Prototypes (Source: Simplification of Liou, 2008)

With this category in mind, it can be said that NCC have tools that enables learning. However, physical prototypes are more suitable for communicating and integrating. Since NCC only uses virtual prototypes, it misses out on the communicative power of physical prototypes.

The practical difference between physical and virtual prototypes can be illustrated by analysing the virtual model BIM. Even though the overall aim of NCC is to implement BIM, a complete information model, the entire organization is not yet utilizing these models. And according to the literature, in the projects where BIM is used, the communicative aspects are arguably not as good as physical prototypes'. BIM and other types of virtual models is found to be good centralized model to collect and store all necessary information for a project. However, this depth of information plus the fact that you need to communicate around a computer screen will arguably limit the communicative abilities. Instead, the ability to put a printed prototype on the table enables you to touch, feel, and comment on the prototype. You will get a better feel for the design and a complete understanding which makes everyone speaking the same language which makes communication easier and more straightforward.

The third variable, supported proactive thinking is explained by Verganti (1999) to consist of for example the use of concept screening checklists, quality function deployment, and - above all - early prototyping. This variable of anticipation capabilities is therefore also dependant on the use of prototypes. At NCC today, various 3D visualization and construction tools are primarily used during the planning and construction phase (phases before the actual construction on site take place), but also when communicating the tendering offers to the client. Therefore the variable of proactive thinking is partly handle by the use of virtual prototypes. But the same reasoning of using physical prototypes as a complement to virtual prototypes can be applied here as well. Using prototypes, physical as well as virtual, the project team can make proactive decisions due to the ability to test, inspect and prove a concept.

The main argument above, of physical prototypes adding value to the projects due to its communicative benefits, is an argument made by assessing the literature regarding prototypes. The benefit of physical 3DP prototypes compared to the present virtual prototypes was unable to be determined by collecting empirical data at NCC, due to the organization's lack of 3DP experience. This may be a reason for criticising the arguments made in this analysis, since it so far has been based on prototype theory alone. However, when looking back at the empirical findings in cycle 1, physical prototypes were observed and argued for, by a 3DP consultant. Examples of prototypes presented were various types of objects, such as toys, houses, wrenches, and a part to be tested before being manufactured using milling. This demonstration showed the strength of prototypes, primarily since you could both look, touch, and feel. They become the centre of attention - a clear communicative benefit.

If NCC wishes to implement 3DP prototypes, the extensive usage of virtual prototypes at NCC of today indicates that implementation can be done with relatively little effort. The project members of NCC are used to work with prototypes, even though they are virtual, and the step to use physical 3DP prototypes is deemed small. A physical 3DP prototype is based on a virtual model, that is converted into 3DP friendly format. Due to the extensive usage of virtual prototypes, there is limited effort to be added if an 3DP prototype is wished for. The large availability of data consisting of virtual prototypes enables a great supply of possible 3DP prototypes as well. Without being naive and recognizing that there are differences, the researchers have a hard time finding a group of people that are more ready to use 3DP than the organization of NCC.

What speaks for low readiness of the organization is obviously that there is limited experience working with physical prototypes. Furthermore, there is an awareness of 3DP as something useful, but since 3DP is primarily a technology that is being pushed out rather than pulled by the market, identifying application areas and knowing when to implement the technology is by nature difficult for the users.

However, the fact that NCC is highly project-based may be a supporting factor for the ability to implement 3DP. Since there a more than 1000 projects each year, testing and experimenting with 3DP can be isolated and thus lower the total risk. What the project-based stricter limits is that each project member might be positive towards 3DP for NCC in general, but not for their projects in particular. Project members may wish to conduct projects as normal instead of taking increased risk by implementing 3DP. A more senior manager overlooking multiple projects may therefore allowing more risk taking in certain pilot projects that can later be compared to other regular project to assess the usefulness further

4.2.5 Refined hypotheses

- The potential users of prototypes has sufficient readiness to use 3DP (Validated)
- A potential area of application for 3DP prototypes is to use it as a tool for communication (to be tested)

4.3 Cycle 3 – How 3DP prototypes may help improve communication of tasks and concepts

The activities performed in the third and iteration cycle put more focus on confronting the theoretical hypotheses with interviews of people working at NCC and their main client Trafikverket (TV). The previous cycle argued for the benefits of using 3DP within the early phases of a project, due to the communicative benefits. This cycle identified and analysed specific usage areas where 3DP prototypes can be used and benefits with the help of its communicative benefits. This cycle thus aims at answering the third research question.

4.3.1 Hypothesis

- A potential area of application for 3DP prototypes is to use it as a tool for communication (to be tested)

4.3.2 Study questions

- Can 3DP prototypes help address the problems related to task communication at the early phases of a construction project?
- Can 3DP prototypes help address the problems related to communication of concept and design at the early phases of a construction project?

4.3.3 Empirical findings

The basis of the data collection in cycle three was the indication in the theory that communication may either be communication of tasks or communication of ideas and concepts. With this categorization in mind, data collection were also focused on a specific project within NCC; modularized bridges. Thus, data about related problems concerning communication of tasks and problems concerning communication of the concept to the client were collected. The structure of the empirical findings is sorted as follows: first, there is a presentation of the modularized bridges to give an overall context of the following data. Second, empirical data about problems associated with the communication of the concept modularized bridges and how an infrastructure project in general is evaluated through public procurement procedures is presented, followed by a presentation of current problems associated with task communication of the said bridge. Intertwined is also different stakeholder's view of using prototypes for both task communication and concept and idea communication.

Modularized bridges

As a measure to increase the productivity, a concept of a modularized bridge with prefabricated concrete elements was developed by NCC. This differs from traditional bridge construction where the concrete elements are casted on site. For the modularized bridges, the prefabricated concrete elements are manufactured in a factory and transported to the construction site. The idea is to have modules with standardized interfaces, which would allow changing and developing the separate modules. The project started in the early 90's, but was put on hold until recently. The investment cost of the bridge itself is higher than a bridge built with conventional methods but potential time savings in terms of shorter construction times is one of the main sell arguments. Another sell argument is that the bridge requires less maintenance, which means that the total life cycle cost is lower.

Except that the bridge faces higher investment costs, there are other obstacles to selling it, such as communicating the design. There are preconceived ideas that a bridge consisting of prefabricated elements looks too much like *the million program,* which was a housing program with the aim to build one million apartments and was issued by the government in Sweden during the 60's. Convincing a potential customer that the bridge has room for change of design is therefore of essence. There are some elements of the bridge that are more critical and more or less define the whole appearance of the bridge, such as the rails on the side and the abutments. These are, compared to the lengths and width or the bridge, not standardized, but rather adjustable and can be designed uniquely to the situation.

A key reason to build modularized bridges is that the builders repeats the same processes in project after project and therefore experience a learning curve. An analogy with IKEA's bookshelf "Billy" is that the first time one builds a Billy the time of construction is long, but the second time shorter and so on. NCC first planned to have one team that went around in Sweden to build the bridges, in order to have experienced personnel, but it was later decided that each local office should be able to build the bridge. Thus, much of the learning curve is gone. During construction of bridges, there have been issues of unanticipated tasks to be done at the construction site. One example was that pre-fabricated concrete element were delivered with the ends of the rebars point up, which then had to be bent on site. This was an activity the was not planned for and had not be anticipated beforehand. Other problems that have occurred during the modularized bridge projects are difficulties in cooperation with external consultants. External consultants are hired to create the main part of the construction planning, i.e. the technical planning, and they see risks in working with new types of concepts, such as the modularized bridge. They prefer working with traditional ways of construction bridges since they are used to. Due to this resistance of change and the unwillingness to cooperate, NCC is creating an internal department for these tasks that consultants were previously needed for.

3DP prototypes for concept and design communicating during the early phases of a project

When selling modularized bridges, they need to go through public procurement procedures since the main buyer, Trafikverket (TV), is a state owned administrative authority. The following section will provide how that process enfolds.

The buyer

The buyer of 80-90 percent of all infrastructure in Sweden is TV, including train rail, roads and traffic control (Trafikverket, 2015**)**. The procurement process of TV is strictly regulated by the public procurement laws in Sweden and the European Union (EU). The rest of the infrastructure projects bought are local municipalities, which follows the recommendations of TV and must also act in accordance with the public procurement laws. TV is split into five units, investments, maintenance, traffic control, planning and large projects. Each unit has its own budget and acts more or less independent.

The different types of contract forms

The process of how an infrastructure project unfolds is highly dependent on which type of contract is used. There are two main types of contracts: execution and turnkey contracts. Historically, TV has used execution based contracts, but has a vision of using turnkey contracts to a greater extent. By 2017, the goal is to issue at least 50 percent turnkey contracts. In short, the constructor (e.g. NCC) are given more degrees of freedom in a turnkey contract, while they are more regulated when execution based contracts are used.

When an execution based contract is used, TV performs all planning and projection for the project. To be more specific, the planning and projection is performed either by TV alone or with help with external consultants. The executor only execute what has already been decided by TV, in colloquial speech TV only hire the executor's "hands and feet". Thus, the executor enters the project rather late in the process. During the tendering process, which follows after the projection and planning made by TV, the executor must show that it has understood the requirements and plans made TV.

For a turnkey project, TV performs some projection but at the end only specifies a list of functional requirements. An example of a functional requirement could be “there is a river at point A, we need a bridge from point B to C on which heavy trucks and tanks (in the event of war) must be able to pass”. Thus, the constructor is able to plan and perform the projection and planning by their own, and the constructor is free to design the said bridge as it wishes. In addition to the turnkey contract an esthetical configuration list may be specified, in order for TV to have more control of the design. The reason to why TV would want to control the design is because of local interests and aesthetic coherence with the surrounding environment. A subset of turnkey contracts is functional contracts, where the constructor also is responsible for the maintenance of the bridge, road and railway.

The process of the tendering process

For all types of contracts, the process begins with an identification of need by TV. A requirement analysis is made, and a building program is created where the demand and prerequisites are presented. The initial phase is followed by a projection phase, which is done regardless of contract form. When using the execution contract form, the projection phase is done with greater detail, while when the turnkey contract type a less detailed projection is carried out. Noteworthy is that the constructor, regardless of contract type, always needs to execute its own projection due to the public procurement laws.

When the technical specifications are specified, TV announces the project whereby constructors may present their solution along with the cost of solution. TV has great freedom to when it comes to defining the level of detail of the technical specification. According to an interviewee at TV, TV often chooses to exclude many of the details in order make the procurement and tendering process easier. Although, this strategy leaves some room for contretemps later on during the project.

The contractors are also allowed to present so called side bids, which is an alternative solution to the original request by TV. In order to present a side bid, a bid on the original solution must be presented. According to an interviewee at TV, side bids are seldom presented.

At the end of the tendering process, TV chooses one or a several winners of the contract, depending on which type of public procurement procedure that was used. Note that the choice of public procurement procedure is distinguished from the choice of type of contract. There are two types of public procurement procedures, the Law of Public Procurement (LPP) and the Law of Public Negotiation (LPN). One winner is chosen if the LPP is used, and one or several is chosen if the LPN is used. If the LPN is used, there is no room for further negotiations, in contrast to LPN. Thus, the contractor and TV may be able to negotiate things such as the price, design and construction time when the LPN is used. LPN is used for railway projects and LPP for all other infrastructure projects.

This negotiation of LPN is performed by a group of people with different expertise. There can be lawyers, engineers, architects just to mention a few. For projects with higher complexity, the number of involved individuals increase. Due to the discretion of LPP, the involved parties is not disclosed. When an offer is won, regardless of the type of tendering process, TV and the contractor meets multiple times to coordinate, plan and cooperate throughout the process from the choosing a contract winner to the completion of the project. During these meetings, the expertise is diversified and the need for clear communication is said to be important.

How a tendering offer is evaluated

Depending on the size of the infrastructure project, hard and soft parameters are valued differently. For larger projects, soft parameters such low noise levels during the construction are valued higher than in smaller projects. For some projects, soft parameters can represent up to 50% of the total value in a tendering offer. Hard parameters are typically costs and time of construction.

How a tendering offer is presented for TV
All tendering offers must be electronically sent to TV, thus it is not possible to present physical objects as part of the offer for TV. TV must receive 2D blueprints as part of the tendering offer, since their database can only store 2D prints. Although, it is possible to add physical objects during LPN negotiations, which is after the initial tendering offer is sent to TV.

After the tendering process is completed
TV and the constructor begin by a starting meeting with people from several different disciplines, such as project managers, architects and local politicians. Unresolved issues are solved and clarifying statements are made. Depending on the size of project and the level of unresolved issues, there are several follow-up meetings before the phase of construction can begin.

3DP Prototypes for task communication during the early phases of a project

The second identified application area is using 3DP prototypes communicating the building process to the people carrying out the project. This could be by printing the bridge with the different elements of the bridge being attachable to visualize the construction order.

It is found that NCC does not reap one of the major advantages of the modularized bridge. One of the main arguments to construct modularized bridges instead of conventional ones is that it will gain repetition effects over time, and that the construction projects are shortened in time due to more effective assembling, similar to the logic of IKEA’s billy shelf, which is not fully addressed since it is stated that all local offices of NCC should be able to build the bridge. By not having the same people constructing the bridge means that the repetition effects diminishes.

From a broader perspective associated with the communication of tasks, a PhD at Chalmers within Visual Management stressed the importance of visually communicating tasks, which is the purpose of using 3DP prototypes in the above described way. According to him, it is not until two or more people have something to react on that problems are brought up and discussed. If two people discuss the process of how to build a bridge, the two people may have two different mental pictures of what they are talking about. Also, people tend to agree with each other if they only use words to communicate.

Although, one interviewee at NCC, who is specialized in the optimization of rebars and concrete, expressed some concerns about using 3DP prototypes for task communication. The primary objection is that communicating tasks with the help of prototypes may be conceived as too childish and trivial for the workers on the building site. If the task of manufacturing a bridge were to be presented using a 3DP prototype, the level of detail need to be high enough to be able to see the rebars. Rebars and other small components of a bridge would thus be too small to be practical to use.

Moreover, when discussing the problems associated with the communication of tasks, two site managers expressed a similar view of using 3DP prototypes to address the problems. One of the interviewee stated that for the prototype to fully address the problems, a logistical perspective must be taken into consideration. The 3DP prototype can therefore not only present the bridge itself, but must be a prototype of the whole construction area, where it is able to visually see where to put certain machines, raw material and how to manage the deliveries of resources.

Finally, and perhaps most interesting, according to two site managers there are no significant problems with the communication of tasks and visualization tools as of today. A slight resistance towards 3DP prototypes is also noticed, with the explanation that for a 3DP prototype to be useful it must not only present the e.g. brige, but also the surrounding environment. There was also concerns about that the builders might perceive the method of visualizing the construction of a bridge using a 3DP prototype with detachable parts as too childish and trivial. Thus, they more or less rejected the idea of using prototypes as a tool for communication to the workers.

4.3.4 Analysis of cycle 3

The following analysis aims to answer the study questions formulated at the beginning at the chapter by combining the empirical finding with literature addressing how uncertainty may be reduced and with literature about task and concept communication.

The empirical findings are centred around the two identified application areas for 3DP; using as a tool to communicate concepts and design, as well as using it as a task communication tool. The analysis follows the same pattern, analysing each application area with regards to the empirical findings and the literature.

Application area: Using 3DP for communication concepts and design

In the analysis of the second cycle, 3DP prototypes were found to have communicative advantages compared to NCC's current usage of primarily virtual models. Arguments were made that due to the benefits of 3DP prototypes, the communicative capabilities are improved as well as improved proactive thinking. The improvement of these two factors is argued to improve the anticipation skills, which is presented as a key capability for successful projects according to Verganti (1999). Arguably, using 3DP for communicating designs and concepts with the client, TV, is an identification of how to apply the benefits of using physical prototypes argued for during the previous cycle.

In the empirical findings, modularized bridges were presented as a specific case to investigate. One main identified problem concerning the modularized bridges is that there are perceived drawbacks of the concept that make working with external stakeholders difficult. Examples of this issue have been that the client may wrongfully associate the bridges with the *million program,* as well as issues working with external consultants who believe there is added risk of working with new, untested concepts. Due to these issues there is an expressed need to be able to communicate concepts and designs better.

Empirical evidence suggest that 3DP prototypes can solve these issues by better communicating the overall concept of an infrastructure project along with specific design details. Specifically, this can be achieved by having a 3DP prototype with detachable parts. By attaching different edge beams, different versions of the modularized brige can be visualised. This is said to better convince the client that the bridge is aesthetically attractive. This is one example of how a physical prototype can communicate designs and concepts. These communicative benefits are in line with Elverum and Welo (2014) among others who speak about prototypes being the most effective tool when convincing internal decision makers and external stakeholders. In particular, Liou (2008) states that prototypes can be used when interacting with customers, which is clearly the case here.

Thus, so far there is an identified need with the organization of NCC and arguably also support within the literature for solving these issues using 3DP. The next step taken is to make an analysis of when and to what extend the implantation of 3DP prototypes is possible. An assumption is that 3DP prototypes may not be suitable for all types of infrastructure projects. Moving from the analysis of solely NCC and the modularized bridges, towards an analysis of the interaction between NCC and TV, a broader understanding of when and how to communicate concepts using 3DP prototypes, is provided.

It is found that NCC can work with TV in many different forms depending on the type of project. A few important factors are found that affect the interface between NCC and TV. As empirical data suggests these aspects are the following.

- Type of public procurement procedure; LPP or LPN.
- Type of contract used; Turnkey or Execution based.
- Complexity of project

By first looking at the differences between LPP and LPN, there is a greater room for negotiation for LPN-project and thus, a greater need for communicating. The virtual prototypes that are used today, which according to Lindlöf (2014) is better to communicate technical properties and may very well be needed, but according to previous analyses physical prototypes better suited to communicate design ideas and concepts when there are many different individual with different perspectives, knowledge and agendas. As found in the empirical data, the process includes people from many different backgrounds such as legal, local politicians and technical specialists. Thus, physical prototypes address the problems associated with communicating a concept and unite a group with many different perspectives.

Moreover, as concluded in the literature section; prototypes are easy to understand for people who are not technically versed. When adding that conclusion with the structure of the early phases of a construction project initiated (where there are people from many different disciplines), the need for prototypes becomes even more apparent. During a project it is found that NCC and TV meets multiple times, to coordinate, plan, and reconcile. Present at those meeting can for example be lawyers, architects as wells as engineers and technical specialist. Due to the different disciplines, a physical prototype put on the table I believed to make everyone speak the same language. The interviewed PhD within visual management argued that visualizing, for example putting a 3DP prototype on the table, triggers rich communication. Also, people tend to agree with each other if they only use words to communicate. According to him, it is not until two or more people have something to react to hat problems are brought up and discussed. Arguably a 3DP prototype put on the table fulfils this purpose.

Turning focus to the difference between turnkey and execution based contracts one finds that the degree of freedom for the constructor in terms of generating own solutions is greater for turnkey contracts. Thus, there is a greater need for the contractor to communicate ideas and own thoughts when turnkey contracts are used. On the opposite, the need for increasing the communicative power when execution based contracts are used is little, since the constructor only needs to respond to the specification given by TV. For these contracts, the uncertainty is found to be low, which limits the need for anticipative capabilities argued for by Verganti (1999).

Adding the two types of contracts with the two different public procurement procedures, one can find an area of application in the intersection of when the LPN and turnkey contracts are used. Using the same logic applied on the intersection between LPP and execution based contracts, the need to increase the communicative abilities is small.

		Type of public procurement procedure	
Type of contract		**LPP**	**LPN**
	Turnkey	Useful	Very Useful
	Execution	Not useful	Useful

Table 10, Type of Procurement Procedure vs. Type of Contract

Furthermore, projects are found to differ n complexity. Data suggest that projects with higher complexity the input for many different areas of expertise and stakeholders is higher than for projects with low complexity. Empirical evidence also shows that that TV leaves out many of the details when presenting the intended project to the different constructors at the beginning of the tendering process, especially in more complex project. For these types of projects, there is a great need for clarification and negotiations even after a bid is won. Connecting the literature of Verganti with prototyping theory, one can draw the conclusion that prototypes could help facilitate to increase the anticipation skills. Prototypes could do this because, as noted in the literature, anticipation skills are much dependent on the ability to communicate, which as already stated one of the main areas of application of physical prototypes. The need for increased anticipation skills lies both with TV and the constructor, but the incentives to increase them lies with the constructor since they are the only ones that have monetary incentives to decrease the cost of the project.

		Complexity of project	
Type of contract		**Low**	**High**
	Turnkey	Useful	Very useful
	Execution	Not useful	Useful

Table 11, Degree of Complexity vs. Type of Contract

Due to the reasoning above, the need for using prototypes when selling modularized bridges, which in this context are rather simple projects, is low. Nevertheless, TV (or the consultants that TV employs) decides which types of bridges that are to be built, and using prototypes when communicating the overall concept of the modularized bridge to the TV or the consultants could be of interest. An implication of that approach is that TV cannot be biased towards a certain constructor, and the only room for communicating the concept of the modularized bridge is within projects. In that setting, a possible strategy could be to present side bids, along with the ordinary bid of the original bridge that was intended be built.

Application area: Using 3DP prototypes for task communication

The second theoretically identified application area is to use 3DP prototypes for task communication. These prototypes are believed to better visualize the tasks to be done by demonstrating these using a 3DP prototype. The key factor with this prototype is that the components that make up the bridge are printed in individual pieces, which can then be attached to each other and thus the bridge is assembled. By letting the employees assemble the prototype the actual tasks to perform later on are effectively communicated.

This application area is supported by the arguments made by Lindlöf regarding visual management. According to Lindlöf (2014), visualization tools can be used to communicate tasks. Visualization is today extensively used within firms to communicate technical properties through the use CAD, 3D-models and prototypes (ibid.).

When looking at the empirical findings it is found that the intentions way to constructing the Modularized bridges using a single national based team to carry out these projects. Instead, each geographical region is set to carry out the construction of the bridges. Due to this, the learning effects that was intended, is being missed. One interviewee explained that these learning effects can be illustrated by the example of Billy book shelves. The assembly of the third one is faster than the first. However, since Ulrich and Eppinger (2012), put learnings as one of the roles of a physical prototype, this may compensated for using 3DP prototype for communicating tasks. The first assembly of a modularized bridge may be speeded up by first visualizing the task with the help of a 3DP prototype.

However, there is also a finding that speaks against using 3DP prototypes for task communication. Site managers who would practically execute the communication stated that the need to increase the communicative ability during the projection and construction phase of a project was small, since the communicative aids used today already is sufficient according to themselves. In addition, it is the site managers that are responsible for the potential task communication using prototypes and the collected belief is that these models face the risk of being too simplistic. The needed detail level is very high, since the construction workers need to be able to see rebars and other details of the bridge. To be able to print with such detail, the printed prototype needs to be larger than what is able to print as of today. Prototypes printed today are not able to show enough detail to add value, and they would be perceived childish to use those as task communication tools.

This analysis is made partly since the workers possess relatively high skill and knowledge. For the other application area, used as a tool for easier communication with the client TV, the knowledge level is different between the individuals in those meetings. Engineers, lawyers, purchasers and project managers can all be part of these meeting and they have different knowledge, which speaks in favour of using 3DP prototypes in those settings. For communicating task, the usability of a 3DP prototype is thus found to be low.

4.4.5 Refined hypotheses

- 3DP prototypes can be used as a tool for communication at the early stages of infrastructure projects, where the LPN and turnkey contracts are used. (validated)

5. Discussion

This chapter presents the discussion that aims at answering and elaborating on the research questions. The structure of the discussion follows the three research questions presented during the introduction chapter of this thesis. The aim of this thesis was to evaluate the usefulness of 3DP and to identify application areas within the case study firm NCC. The discussion is based on the findings from the interviews in NCC, the external perspective interviews and the literature study.

1. What is the current state of development of 3DP when applied to the construction industry?

3DP is not only a solution to a so far unknown problem it is also a hyped technology. The availability of printers is wide and the believed benefits in the future are supposed to be revolutionary. What kind of problems to solve using 3DP are not as clear. In contrast to the hype, it is found that most of these believed benefits of 3DP are not available as of today. Rather the printed parts are most often small, made in plastic and takes too long time to manufacture. Yes, there are benefits such as flexibilities in design, high geometric complexity, reduced number of manufacturing steps needed and less material usage. However as an end-manufacturing tool the usage areas are limited, which is confirmed by both 3DP specialist and the literature. When using 3DP for end components one needs to adhere to the constraints of the technology, primarily limitations in choice of materials and size.

When assessing the technology readiness using the TRL-framework of end component usage of 3DP one must therefore make specific analyses and assessments for each industry. For example the dental industries, the technology readiness is arguably be high, close to a level of nine, since 3DP as a production method has reached full commercialization. For the case study firm NCC, which operates in the construction industry, the readiness end components with 3DP is substantially lower. Although, it is found that the readiness for plastics in particular is higher, indicating that the technological development has come further for prototypes which are mainly done with plastics as input material.

The first indications of low readiness of 3DP as an end manufacturing tool is shown in the Gartner group's hype cycle (see Figure 1). There it is clearly found that most application areas for 3DP are two to five or even up to ten years from maturity. Further media hype is provided by Starr (2015) who speaks of entire houses made by 3D printers in the future, and concrete extrusion robots (Lim et. al 2015). The notion of pro-innovation bias is apparent here. Few indications of the robustness is presented, nor if it possible to integrate rebars, electricity, and insulations. The writings about the steel joint created by the engineering firm Arup, follow the same biased evaluation. The steel joint is indeed an interesting design and geometric solution. But no statements regarding the quality factors such as durability or load bearing abilities are presented. This might be due to over enthusiasm regarding the technology, in line with the concept of pro-innovation presented by Rogers (2003).

When adding the concepts of TLC one finds that end-components for the construction industry is in particular low, since the only 3DP:s that are applicable in the construction industry are prototypes and more or less only robots with an automatic extrusion of concrete.

Furthermore when looking at the limiting factors of the construction industry, it is clearly stated that the products of NCC are generally large and load bearing. The construction industry in general is highly regulated and the demands for durability are extreme. For example a bridge constructed today is expected to last for 120 years. Materials and components used needs to be certified and proved to last. This leads to an obvious mismatch between the construction industry and end components manufactured by a 3D Printer. The technology readiness of 3DP as an end manufacturing technology is therefore low.

2. What are typical problems in the early phases of projects, how does NCC address these where is there room for improvement?

By using the statements made by Verganti (1999), three factors that define the anticipation skills were analysed, since the outcome of a project is dependent on the outcome of the early phases and those in turn are dependent on the anticipation skills. It was found that one of the main problems that NCC does not sufficiently address is the communicative aspects, mainly due to the fact that they only use virtual prototypes which according to the prototyping theory do not support communication effectively. A hypothesis that 3DP prototypes may help improves the anticipation skills by improving the communicative abilities was thus formulated.

3. What is an area of application for 3DP at NCC, a large construction firm?

As outlined in the literature, there are two main areas of applications for 3DP, end-components and prototypes. A clear area of application for end-components was not found, mainly due to the high demands for durability and that NCC must prove that the components lasts for many years. However, the study was centred on a few cases, such as end-beams and pole-shoes. One of the main problems of finding cases where 3DP could be used for end-components is the one that is inherent when looking at pushed technology: it is difficult to find areas of application. A greater sample size, where substantial efforts were put into brainstorming sessions could have generated a large sample size, and thus, perhaps a different conclusion.

On the other hand, when looking at prototypes used in projects issued by TV, the usefulness depends on which type of public procurement procedure and which contract that is used by TV. The usefulness for projects where LPP and execution based contracts are used is low, due to the fact that the need to communicate and reduce uncertainty is low. For projects where the need to resolve issues and different branches of expertise must understand each other, the usefulness of 3DP prototypes is high. Such projects are when the LPN and turnkey contracts are used.

Due to the same logic, projects where the modularized bridge is applicable may be too simple, but there is a clear need for NCC to communicate the concept to TV; thus there could be an area of application when presenting the overall concept to TV, and not within specific projects where the modularized bridge is applicable. However, communicating the concept must be done through specific projects due to the public procurement laws where TV cannot be biased towards a particular constructor. The concept must therefore be presented through specific projects, possibly by presenting side bids along with the originally requested bridge. This also means that NCC must reveal their invention before it may be commercialized.

When finding possible areas of application, one must also take into consideration how the prototypes could be used in coexistence with the current visualization strategy, which is focused around using BIM-models. It is possible that some of the advantages of physical prototypes and BIM-models may overlap. Although, there are few incentives not to add physical prototypes when communicating with TV within highly complex and large projects where the rewards of improving the early phases is high. After all, according to Verganti, the outcome of the project in whole is very much dependent on the performance and outcome of the early phases. Thus, small investments and small gains in the early phases may result in large savings and large gains of the whole project.

Using the Customer Development Process

In addition to the findings regarding 3DP technology, this study has used a method that can be of general interest for NCC. Using a hypothesis driven customer development model for an internal investigation to find an area of application has both advantages and disadvantages. This model is then of interest to be discussed if NCC aims to continue to follow the process. The advantages are that the customer development process is a structured, but inherently flexible, process where all accumulated learnings are internalized in the hypotheses. When approaching a fuzzy and vague task such as finding an area of application for a new technology, the Customer Development Process is therefore useful.

The drawbacks could be that there is no clear goal or a clear stop when to stop iterating, where the researcher must possess much integrity and be confident when to stop. Using the term “stop” could nevertheless be misinterpreted and misused, since organisations must keep evolving and develop in order to stay competitive. A second disadvantage is that it almost exclusively (at least for this study) draws on internal capabilities and resources. A complementing study could be to study the surrounding environment of the company in question, such as looking at how existing and new competitors utilize the new technology. A third disadvantage that was found during the interviews was that employees do not want to talk about their problems, but rather wants to hear about the possibilities with the new technology. The appropriability of the customer development process in that context could be questioned and the skills of the researcher must be high in order to extract the problems that the interviewee faces in his or her daily work.

Since there is no definite stop or clear goal for a customer development process, this thesis is no exception. When looking at this specific study, further cycles can be defined. In a future cycle five, where NCC inherit the hypotheses from cycle four, and (as already mentioned in the discussion) follow a project where 3DP prototypes can be implemented. This project should then be documented to be able to observe the change when introducing a 3DP prototype in a project. This would validate the statements concerning the increased communicative advantages.

Realizing that 3DP is probably not the only new technology that will be pushed into the market, future use of this hypothesis driven approach at NCC could be appropriate when analysing the applicability of new technologies. Internalizing the learnings of this research would in that case be of importance.

6. Conclusions

The aim of the study was to assess the potential and to find areas of application of 3DP at NCC. 3DP is considered to be a solution to a so far unidentified problem. In order to assess the state of technological development and identify areas of application, a hypothesis-driven Customer Development Process has been used. This led to the iteration of three cycles in order to answer the three research question of this study. This study found that the 3DP can be used either to make end-components or to make prototypes. For the construction industry in particular, the state of the technological development of 3DP for end-components is low, while the readiness is high for prototypes. The technology in general is currently in a state of era of ferment, where there are many actors and technologies currently on the market, especially for 3DP applied in the construction industry. 3DP End-components were placed at the beginning at the S-curve, while prototypes were placed higher up. n area of application for 3DP prototypes is as a tool for communicating ideas, design and concepts to the client. The usefulness is high in projects where the complexity is high and where the Law of Public Negotiation (LPN) and turnkey contracts are used. The main limitation of this study is that the empirical data has only been collected from the division that sells and produces infrastructure projects. Future research about investigating the usefulness of 3DP in the construction industry could be focused on housing and development divisions within construction companies.

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