GRADUATION PROJECT

THE FIRST STEPS TOWARDS SUCCESSFUL IMPLEMENTATION OF AR IN THE DUTCH CONSTRUCTION SECTOR

THE MOST IMPORTANT OBSTRUCTIONS CONCERNING THE IMPLEMENTATION OF AR IN THE CONSTRUCTIONS INDUSTRY

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Summary

The construction industry realizes the urgent need for providing the opportunity to understand the current project status easy, rapid, and accurate. Currently, manual visual observations and traditional progress monitoring based on field personnel's interpretation are time-consuming, error-prone, and infrequent. For that reason, the building sector is replacing traditional monitoring methods with automated solutions. These automated solutions generate large amounts of data (Big Data), which can only be surmounted by advanced methods of visualization. Since the construction sector is lagging behind concerning the processing of Big Data and the implementation of automated solutions, it is necessary to develop new methodologies to visualize construction-related datasets. A relatively new and promising method of automated monitoring, that converges with Big Data, is Augmented Reality (AR). Further research into the implementation of AR addresses the demand for new interactive platforms and methodologies to visualize construction-related datasets.

However, AR is still relatively in its early stages of development pertaining to the construction industry, and it's already showing great potential. The implementation of this technology looks like the definite future for the construction industry, despite some present obstructions that slow down its implementation, the possible applications are promising, such as visualization of technical information on the job site, and visualization of a spatial model for design and marketing.

In order to identify the obstructions that are currently slowing down the implementation of AR, Theoretical, and Qualitative research were conducted. First, theoretical research was conducted by literature research on the following topics concerning the (Dutch) construction sector: Augmented Reality, (automated) monitoring and Big Data concerning AR-systems. Then qualitative research was conducted in the form of interviews with experts on the topic (of AR) from different fields of expertise in and outside the construction sector. Data derived from the theoretical and qualitative research was structured and categorized using the Grounded Theory, resulting in a list with the obstructions and enablers per source. Because the obstructions were derived from two sources (literature research and qualitative research), Methodological Triangulation was used to see if similar results could be found, establishing validity.

After triangulation of the data, the definite list of obstructions per category was established and used in the survey for ranking the obstructions. Every statement concerned an obstruction regarding the implementation of AR in the construction industry. The survey was then presented to experts on the topic, who graded the obstructions according to their perceived level of importance, using one of the five linguistic terms, that used a 1-9 scale for the corresponding fuzzy numbers. With regard to the experts, three areas of expertise were distinguished. The scale determined the relative importance (weight) of an obstruction when compared with another alternative. Structuring the survey in such a way, made it possible to use Fuzzy TOPSIS method for analyzing the data and calculating the ranking of the obstructions. In order to identify similarities and differences between the different fields of expertise, the data per field of expertise was kept separate, so it was possible to apply data triangulation again.

Eventually, using the Fuzzy TOPSIS method resulted in the top 3 most important obstructions; (1) poor information management, (2) invisibility of the added value, and (3) uncertainty about Return on Investment (RoI).

Then, the relevant enablers, regarding the three most important obstructions, were established and discussed with an expert on the matter, in order to choose the best enablers for a practical recommendation, regarding the first steps towards successful implementation of AR in the construction industry. Eventually, the enablers: set up a universal AR protocol, exemplary use cases, and organization based funding were found to be the best possible fit as a starting point for giving a practical recommendation, on overcoming the three most important obstructions, concerning the implementation of AR in the construction industry.

Because the implementation of AR is a very comprehensive problem, it wasn't realistic to provide a ready-made solution only based on this research. Therefore, the main research question was answered in the form of a directional and practical guide, describing the first possible steps/points towards successful implementation, intended for contractors within the construction industry. Using the three previously mentioned enablers as a guideline.

Samenvatting

De bouwsector beseft dat er dringend behoefte is om de huidige projectstatus gemakkelijk, snel en nauwkeurig te begrijpen. Momenteel, zijn handmatige visuele observaties en traditionele voortgangsbewaking, op basis van de interpretatie van operationeel personeel, tijdrovend, foutgevoelig en onregelmatig. Om die reden, vervangt de bouwsector haar traditionele monitoringmethoden door geautomatiseerde oplossingen. Deze geautomatiseerde oplossingen genereren grote hoeveelheden gegevens (Big Data), die alleen kunnen worden verwerkt door geavanceerde visualisatiemethoden. Omdat de bouwsector achterloopt met betrekking tot de verwerking van Big Data en de implementatie van geautomatiseerde oplossingen, is het noodzakelijk om nieuwe methoden te ontwikkelen om bouw gerelateerde datasets te visualiseren. Een relatief nieuwe en veelbelovende methode van geautomatiseerde monitoring die samengaat met Big Data, is Augmented Reality (AR). Verder onderzoek naar de implementatie van AR speelt in op de behoefte naar nieuwe interactieve platforms en methoden om bouw gerelateerde datasets te visualiseren.

AR bevindt zich echter nog steeds in een relatief vroeg ontwikkelingsstadium binnen de bouwsector, maar biedt echter al veel potentieel. De implementatie van deze technologie lijkt de definitieve toekomst voor de bouwsector, ondanks obstructies die implementatie van de technologie vertragen, zijn de mogelijke toepassingen veelbelovend, zoals visualisatie van technische informatie op de bouwplaats en visualisatie van een ruimtelijk model voor ontwerp en marketing.

Om de obstructies te identificeren, die momenteel de implementatie van AR vertragen, werd theoretisch en kwalitatief onderzoek uitgevoerd. Eerste werd theoretisch onderzoek uitgevoerd op basis van literatuuronderzoek, naar de volgende onderwerpen met betrekking tot de (Nederlandse) bouwsector: Augmented Reality, (geautomatiseerde) monitoring en Big Data betreffende AR-systemen. Vervolgens werd kwalitatief onderzoek uitgevoerd, in de vorm van interviews met experts uit verschillende expertisedomeinen in en buiten de bouwsector, aangaande AR. De verkregen gegevens, uit het theoretische en kwalitatieve onderzoek, werden vervolgens gestructureerd en gecategoriseerd met behulp van de Grounded Theory, resulterend in een lijst met obstructies en enablers per databron. Omdat de obstructies werden afgeleid uit twee bronnen (literatuuronderzoek en kwalitatief onderzoek), werd Methodologische Triangulatie gebruikt om te zien of vergelijkbare resultaten konden worden gevonden en deze te valideren.

Na triangulatie van de gegevens, werd de definitieve lijst van obstructies per categorie opgesteld en gebruikt in de enquête ter beoordeling. Elke verklaring betrof een obstructie met betrekking tot de implementatie van AR in de bouwsector. De enquête werd vervolgens gepresenteerd aan experts op het gebied van AR, die de obstructies beoordeelden op basis van belangrijkheid in hun perceptie, met behulp van een van de vijf ordinale termen, die een schaal 1-9 gebruikten voor de gerelateerde fuzzy-getallen. Betreffende de experts, werden drie expertisegebieden onderscheiden: Consultancy Bureaus (bouw gerelateerd), Aannemers (bouw gerelateerd) en Industrie (niet bouw gerelateerd). De schaal bepaalde het relatieve belang (gewicht) van een obstructie in vergelijking met een ander alternatief. Door de enquête zo te structureren, kon de Fuzzy TOPSIS-methode worden gebruikt om de gegevens te analyseren en de rangorde van de obstructies te berekenen. Om overeenkomsten en verschillen tussen de verschillende expertisegebieden te identificeren, werden de gegevens per expertisegebied gescheiden gehouden, zodat het mogelijk was om data triangulatie opnieuw toe te passen.

Uiteindelijk resulteerde het gebruik van de Fuzzy TOPSIS-methode in de top 3 van belangrijkste obstructies; (1) slecht informatiebeheer, (2) onzichtbaarheid van de toegevoegde waarde en (3) onzekerheid over Return on Investment (RoI).

Vervolgens werden de relevante enablers, met betrekking tot de drie belangrijkste obstructies, vastgesteld en besproken met een expert uit de aannemerswereld, om de beste enablers te kiezen voor een praktische aanbeveling, met betrekking tot de eerste stappen naar een succesvolle implementatie van AR in de bouwsector. Uiteindelijk bleken de enablers: het opzetten van een universeel AR-protocol, voorbeeld use-cases en organisatie gebaseerde financiering de best mogelijke uitgangspunten, voor het geven van een praktische aanbeveling voor het overwinnen van de drie belangrijkste obstructies, met betrekking tot de implementatie van AR in de bouwsector.

Omdat de implementatie van AR een zeer uitgebreid probleem is, was het niet realistisch om een kant-en-klare oplossing te bieden op basis van dit onderzoek. Daarom werd de belangrijkste onderzoeksvraag beantwoord in de vorm van een directionele en praktische gids, waarin de eerste mogelijke stappen/punten, voor een succesvolle implementatie werden beschreven, bedoeld voor aannemers in de bouwsector. Waarbij de drie hierboven genoemde enablers als richtlijn. Waarbij de drie hierboven genoemde enablers als richtlijn.

Abstract

The construction industry is realizing the urgent need for providing the opportunity to understand the current project status easy, rapid, and accurate. Currently, manual visual observations and traditional progress monitoring based on field personnel's interpretation are time-consuming, error-prone, and infrequent. For that reason the building industry is replacing the traditional monitoring methods by automated solutions. These automated solutions generate large amounts of data (Big Data) which can only be surmounted by advanced methods of visualization, particularly Augment and Virtual reality technologies. Since the construction industry is lagging behind concerning the processing of Big Data and the implementation of automated solutions, it is necessary to develop new methodologies to visualize construction-related datasets. A relatively new and promising method of automated monitoring that converges with Big Data, addressing the problem, is AR (Augmented Reality). Further research into the implementation of AR, addresses the demand for new interactive platforms and methodologies to visualize construction-related datasets supporting wider AR adoption.

The research objective of this study is to examine the potential of AR within the Dutch construction industry focusing on the first steps towards the successful implementation of AR and thereby wider AR adoption. Firstly, the current state of AR in the construction industry, especially the Dutch construction industry, is determined. Secondly, the benefits of using AR in the construction industry are specified. Thirdly, it's determined to what construction stages the implementation of AR is of concern. Fourthly, obstructions that are encountered when implementing AR are established and ranked. Fifthly and as of last, the enablers of the most important obstructions are specified and it's explained how they can be overcome.

List of Abbreviations

AEC:	Architects, Engineers, and Contractors
AHP:	Analytic Hierarchy Process
AR:	Augmented Reality
CC:	Closeness Coefficient
D4AR:	4 Dimensional Augmented Reality
FNIS:	Fuzzy Negative Ideal Solution
FPIS	Fuzzy Positive Ideal Solution
GTA:	Grounded Theory Approach
MCDA:	Multi-Criteria Decision Analysis
MR:	Mixed Reality
PROMETHEE:	Preference Ranking Organization Method for Enrichment Evaluations.
RoI:	Return on Investment
USP:	Unique Selling Points
VR:	Virtual Reality

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Introduction

This chapter introduces the topic of this thesis, Augmented Reality in the construction industry.

1. Introduction

In this chapter the main subject, Augmented Reality (AR) in the construction industry, is introduced. First, it's explained how the topic was found and why research on the topic is important. Followed by the research problem, creating an impression about the area of concern. Then, one main research question and five sub research questions, were established for improving knowledge on the topic. The research objective and limitations summarize what is hoped to be achieved by this study and what the shortcomings of the research are. As of last, the research design provides the framework of methods and techniques to handle the research problem.

1.1. Research importance

The construction industry is responsible for undertaking some of the biggest and most expensive projects on Earth. Huge amounts of resources and work go into major construction projects and of course this means that huge volumes of data are generated (Marr, 2016). The ability to process these large amounts of data and to extract useful insights from data has revolutionized society. This phenomenon—dubbed as Big Data—has applications for a wide assortment of industries, including the construction industry. The construction industry already deals with large volumes of heterogeneous data; which is expected to increase exponentially as technologies such as sensor networks and the Internet of Things are commoditized (Bilal, et al., 2016).

Construction progress monitoring can be regarded as the ongoing, key tasks in construction processes (Golparvar-Fard, Bohn, Teizer, Savarese , & Peña-Mora, 2011; Yang , Park, Vela, & Golparvar-Fard, 2015). It involves periodic measurement of the actual progress of a project and its comparison with expected progress (Alizadehsalehi & Yitmen , 2018; Hwang, Zhao, & Ng, 2013). Accurate and timely information of construction project progress in a regular repeated basis (Big Data) is one of the critical stages of construction management. Progress monitoring is considered as one of the most challenging tasks due to the complexity of goals and interdependency of activities (Alizadehsalehi & Yitmen , 2018).

The construction industry realized the urgent need for providing the opportunity to understand the current project status easy, rapid, and accurate (Bosché, Ahmed , Turkan, Haas, & Haas, The value of integrating Scan-to-BIM and Scan-vs-BIM techniques for construction monitoring using laser scanning and BIM: The case of cylindrical MEP components, 2015). Rapid project assessment further identifies discrepancies between the as-built and as-planned progress, and facilitates decision making on the necessary remedial actions (Fard, Peña-Mora, & Savarese, 2011). Further, accurate assessment of progress allows managers to make adjustments to minimize costs when deviations from the schedule occur (Kopsida , Brilakis , & Vela, 2015). Currently, manual visual observations and traditional progress monitoring based on field personnel's interpretation are time-consuming, error-prone, and infrequent (Golparvar-Fard, Mora , Arboleda, & Lee, 2009; Navon & Sacks, 2007) (Alizadehsalehi & Yitmen, 2016). In combination with the continually increasing complexity of projects, progress monitoring methods are changing. The construction industry is replacing the traditional monitoring methods by automated solutions, to accomplish this task (Skibniewski, 2014).

Recent advances in information and communication technologies have enabled researchers to make considerable efforts toward improving the efficiency and quality of project progress control (Bosché, Ahmed, Turkan, Haas, & Haas , 2015; Son, Bosché, & Kim, 2015). These methods and technologies support conventional tasks, ease communications, speedup processes, and manage information efficiently. Automation of project progress control and monitoring process is a great interest to construction industry practitioners since it will aid them in overcoming the limitations associated with presently employed manual data collection and analysis practices (Zhang & Arditi, 2013; Kim, Son , & Kim , 2013). Recently, researchers have attempted to automate the process of construction performance monitoring by leveraging advances in computer vision, robotics, and construction management. Despite recent advances in technologies and equipment for automated progress monitoring, most construction companies worldwide do not utilize them for their projects. This can be due to several reasons, such as the high cost of technologies and equipment, implementation issues, need for skilled staff, and, most importantly, a lack of sufficient information about the impact of automated progress monitoring in comparison with conventional progress monitoring on project performance control (Alizadehsalehi & Yitmen , 2018).

Automated project progress monitoring involving an automated approach for recognition of physical progress, accurate and efficient tracking, and analysis and visualization of the as-built (actual) status of buildings under construction—which are critical components of successful project monitoring—is a valuable tool for construction progress monitoring. Site data collection technologies could potentially automate all steps of collecting, analyzing, and representing progress and recognize its deviations from a construction.

However, there is still a need to further develop the technologies, software, and algorithms and determine all the factors that affect the automated progress monitoring of the construction projects. Exploring the influence of data capture and collection technologies in automated progress monitoring control on other important dimensions of project performance control (Alizadehsalehi & Yitmen , 2018).

As said, automated progress monitoring generates timely information of construction project progress in a regular repeated basis (Big Data). However, the adoption of Big Data technology in the construction industry lags the progress made in other fields. With the commoditization of the technology necessary for storing, computing, processing, analyzing, and visualizing Big Data, there is immense interest in leveraging such technologies for improving the efficiency of construction processes (Bilal, et al., 2016).

Data-driven analytics have long been used in the construction industry due to the broad applicability of such techniques in many construction subdomains, the adoption of the recent, much agiler and powerful, Big Data technology has been relatively slow. Although Big Data trend is gradually creeping in the industry; its applicability is amplified further by many other emerging trends such as BIM, IOT, cloud computing, smart buildings, and augmented reality, which are also slightly elaborated (Bilal, et al., 2016).

Bilal et al. presented some of the prominent future works along with potential pitfalls associated with Big Data while adopting it in the industry. One of the prominent future works and potential opportunities mentioned is Big Data and AR (Augmented Reality) enabled As-planned vs. As-built comparison system. Aligning with the need to further explore the influence of data capture and collection technologies in automated progress monitoring control (Bilal, et al., 2016).

Augmented reality (AR), which is an offshoot of virtual reality, is the field in which computer-generated virtual objects are superimposed over real-world scenes to produce mix worlds. It enables a semi-immersive environment that accurately aligns real scenes with corresponding virtual world imagery. This mixed overlay enables the users to obtain additional information about the real world. It is an emerging technology for enhancing human perception (Bilal, et al., 2016).

In augmented reality, computer software must derive real-world coordinates, independent from the camera or from camera images. Augmented reality in construction and architecture projects involves placing a 3D model of a proposed design onto an existing space using mobile devices and 3D models (Yoders, 2018).

Hence, AR and Big Data inevitably converge. The complexity associated with Big Data in construction is enormous, which can only be surmounted by advanced methods of visualization, particularly Augment and Virtual reality technologies. Four pillars for wider AR adoption in the construction industry can be pointed out. (i) Localization, the ability to accurately impose virtual object on the real-life scene. (ii) A natural user interface, which provides easy and intuitive user experiences to increase the usability of AP software. (iii) Cloud computing, which enables apps to store and retrieve information seamlessly everywhere, and (iv) mobile devices, which are getting smaller, cheaper, and powerful and play a vital role in AR environment (CH, Kang, & Wang, 2013). Supporting wider AR adoption requires new interactive platforms and methodologies to visualize construction related datasets (Bilal, et al., 2016).

1.2. Research problem

The construction industry is realizing the urgent need for providing the opportunity to understand the current project status easy, rapid, and accurate (Bosché, Ahmed , Turkan, Haas, & Haas, 2015). Currently, manual visual observations and traditional progress monitoring based on field personnel's interpretation are time-consuming, error-prone, and infrequent (Golparvar-Fard, Mora , Arboleda, & Lee, 2009; Navon & Sacks, 2007) (Alizadehsalehi & Yitmen, 2016). For that reason the building industry is replacing the traditional monitoring methods by automated solutions (Skibniewski, 2014). These automated solutions generate large amounts of data (Big Data) which can only be surmounted by advanced methods of visualization, particularly Augment and Virtual reality technologies. Since the construction industry is lagging behind concerning the processing of Big Data and the implementation of automated solutions, it is necessary to develop new methodologies to visualize construction related datasets. (Bilal, et al., 2016; Alizadehsalehi & Yitmen , 2018). A relatively new and promising method of automated monitoring that converges with Big Data, addressing the problem, is AR Further research into the implementation of AR, addresses the demand for new interactive platforms and methodologies to visualize construction related datasets.

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1.3. Research questions

Main research question:

What are the first steps towards successful implementation of AR (Augmented Reality) in the Dutch construction industry?

Sub research questions:

- **Sub question 1:**
  What is the current state of AR in the construction industry?
- **Sub question 2:**
  What are the benefits of using AR in the construction industry?
- **Sub question 3:**
  What are the construction stages of interest concerning the implementation of AR?
- **Sub question 4:**
  What obstructions are encountered when implementing AR in construction projects?
- **Sub question 5:**
  What are the enablers that can help to overcome the most important obstructions?

1.4. Research objective and limitations

The research objective of this study is to examine the potential of AR within the Dutch construction industry focusing on the first steps towards successful implementation of AR and thereby wider AR adoption. Firstly, the current state of AR in the construction industry, especially the Dutch construction industry, is determined. Secondly, the benefits of using AR in the construction industry are specified. Thirdly, it's determined to what construction stages the implementation of AR is of concern. Fourthly, obstructions that are encountered when implementing AR are established and ranked. Fifthly and as of last, the enablers of the most important obstructions are specified, and it's explained how they could be overcome.

The following research limitations are identified:

- Because of the limited time, not all articles about the topics can be taken into consideration. However, every effort is made to include the most important and relevant topics.
- Not every expert on AR within the construction industry can be interviewed.
- The survey size for experts on AR within the construction industry can't be met, because of the high sample size (standard sample size formula) and the limited number of experts on AR within the industry.
- Survey size for experts outside the construction industry will not be met, because they are purely included for indicating a possible different or advanced view/approach on the topic.
- The research distinguishes two main fields concerning AR in the construction industry; consultancy/engineering bureaus and contractors.
- The research generalizes the experts out of the non-construction related fields, so they are seen as one group.
- The results are based on the weight given by all the experts combined. Hence, all fields of expertise combined provide the final results concerning the weighting of the obstructions.
- The report was mainly written focused on contractors within the construction industry.

1.5. Research design

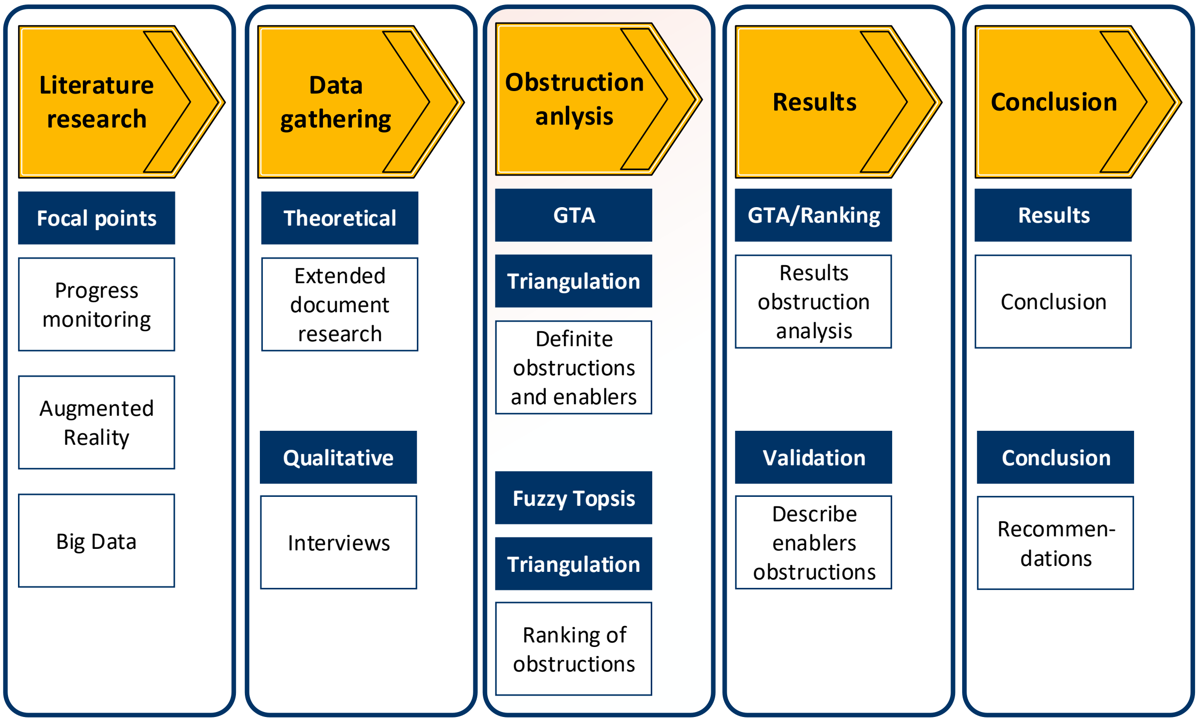

Figure 1, Research design

This research consists out of five main components (figure 1): Literature research, Data gathering , Obstruction analysis, Results, and the Conclusion. Within the literature research, **chapter 2**, three focal points are distinguished; progress monitoring, augmented reality and big data. In this chapter, the first two and partly the third research question are answered.

In **chapter 3,** the methodical justification can be found. Herein, the theory and methods to identify and analyze the obstructions, concerning the implementation of AR, are explained. This includes the following theories: the Grounded Theory Approach (GTA), the Fuzzy TOPSIS method, and data triangulation of the outcomes.

The data for the obstruction analysis in **chapter 4** is obtained by theoretical research, using the literature research supplemented with document research, and by qualitative research in the form of interviews. This data is then processed and coded using the Grounded Theory Approach (GTA). To identify possible similarities in the codes, data triangulation is applied per category. These categories are formed by selective codes. When the definite obstructions and enablers are established, the obstructions are ranked using the Fuzzy TOPSIS method. A survey is designed and send out to experts, in order to facilitate this method. By keeping the data sources separated applying triangulation, in order to identify similarities and differences between the different fields of expertise, is possible.

Chapter 5, describes the results emerging from the analysis. First, the results from the obstruction analysis are described, primarily based on the GTA and ranked obstructions. Answering the second part of the third research question and the fourth question. Next, the enablers for the most important obstructions are validated and described, answering the fifth research question.

The research is summarized in the conclusion, **chapter 6**. With as guideline the main answers to the five research questions. Finally, some propositions and recommendations for future work are discussed.

Because of the large amount of additional information, only the essential documents are provided in the appendix of this report. Therefore, a supplement report, including all the information is provided, making this report easier to read and less bulky.

Literature review

This chapter displays the literature research, with as main aspects: (automated) progress monitoring, Augmented Reality, and Big Data

2. Literature review

This literature review consists out of four main subjects: Progress monitoring, Automated progress monitoring, Augmented reality and Big Data and AR. Chapter 2.1., of the literature research describes the current situation concerning progress monitoring in the construction industry and why the industry is replacing traditional monitoring by automated monitoring. Then, in chapter 2.2., the general concept of automated monitoring in the construction industry is discussed. Thereafter, in the sub-chapters: Data acquisition (2.2.1.), Information retrieval (2.2.2)., Progress estimation (2.2.3.) and Visualization (2.2.4.), different methods of automated monitoring are highlighted. In sub-chapter synthesis (2.2.5.), different methods of automated monitoring are compared with each other based on certain criteria. In the last sub-chapter 2.2.6. it's concluded that Augmented Reality is currently the most promising automated monitoring solution. Chapter 2.3. elaborates further on the topic Augmented reality. Describing the pros and cons using the sub-chapters: Intersection between conscious real and virtual, Opportunities/functionalities, Integration and Sub-conclusions concerning Augmented Reality. Automated solutions generate large amounts of data (Big Data) which can only be surmounted by advanced methods of visualization, particularly Augment and Virtual reality technologies. Since the construction industry is lagging behind concerning the processing of Big Data (Bilal, et al., 2016; Alizadehsalehi & Yitmen , 2018) and the capability of processing data has a large impact on the use of Augmented Reality, the last chapter 2.4. discusses Big Data and AR. Herein, the current data processing state of the construction industry is described. Also in the last sub-chapter a sub-conclusion conerning Big Dat and AR is drawn.

2.1. Phases of a construction project

As stated in the introduction the construction industry is realizing the urgent need for providing the opportunity to understand the current project status easy, rapid, and accurate (Bosché, Ahmed , Turkan, Haas, & Haas, 2015). On-site progress monitoring is essential for keeping track of the ongoing work on construction sites. Construction can be understood as the materialization – physical realization of the project documentation (Duston & Shin, 2009; Meza , Turk, & Dolenc, 2013; Turk Z. , Phenomenological foundations of conceptual product modelin in architecture, engineering and constructio., 2001). Construction monitoring is an accurate and positive way of checking the quality, accuracy and progress of a construction project (SGS, 2019). Currently, this task is a manual, time-consuming activity (Brann, Tuttas , Borrman, & Stilla , 2014). The phases of a construction project (see figure 2) generally consist out of the following phases:

- Phase 1: Identify policy need and how to meet this need
- Phase 2: Draw up of project brief (market demand/imitation and sketch design)
- Phase 3: Development of delivery strategy (development of the design)
- Phase 4: Draw up of design brief (contract and pre-construction)
- Phase 5: Actual construction
- Phase 6: Operate and maintain
- Phase 7: Disposal and decommissioning

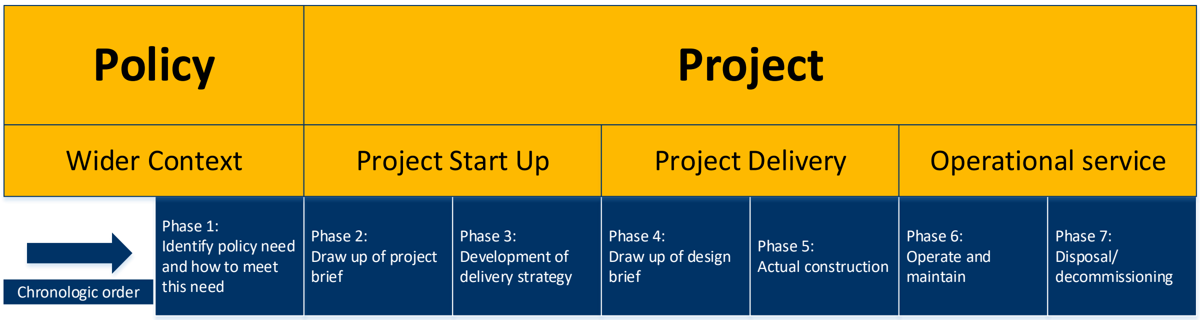

Figure 2, Construction project phases (Dawood, 2009)

2.2. Progress monitoring

Monitoring and controlling a construction project according to the Project Management Body of Knowledge "consists of those processes required to track, review, and orchestrate the progress and performance of a project: identify any areas in which changes to the plan are required; and initiate the corresponding changes". These processes involve the measurement of the progress through inspections and the comparison with the project plan in order to validate the predicted performance. Progress monitoring is considered as a critical success factor for projects to be delivered on time and within budget (Iyer & Jha , 2005) and as one of the most difficult tasks due to the complexity and interdependency of activities. (Saidi , Lytle , & Stone , 2003; Zhang, et al., 2009) (Kopsida, Brilakis, & Vela, 2015).

Accurate and timely information of the progress in a regular repeated basis is needed for a well maintained and efficient project control that will ensure cost and time efficiency of the project. Hence, an efficient on site data collection, a timely data analysis and a communication of the results in a well interpreted way are major concerns for construction companies (Saidi , Lytle , & Stone , 2003). Regular repeated inspections allow managers to identify deficiencies in an early stage, prevent potential upcoming delays because tasks are linked, and make timely decisions for corrective actions (Maalek & Sadeghpour, 2012). As a result, the possibility of unpredicted costs from delays, reworks, disputes and claims (Yates & Epstein , 2006) are mitigated (Semple, Hartman, & Jergeas, 1994). On the other hand, insufficient management and low quality control can cause delays, decrease in project profitability, cost increase (Zavadskas , Vilutienė, Turskis, & Šaparauskas, 2014) and have severe impacts on productivity (Yi & Chan , 2006). The time it takes to identify the discrepancies between the as-planned and as-built model is proportional to the cost and to the difficulty to implement corrective measures. (Navon & Shpatnitsky, 2005) (Kopsida, Brilakis, & Vela, 2015).

Conventional data collection and activity progress monitoring depend mostly on daily or weekly reports of foremen uploaded to a computer after analysis of these reports. Despite the importance of progress monitoring, the conventional method can be challenging because it is expensive, ineffective (Zhang & Arditi, 2013; Braun, Borrmann , Tuttas , & Stilla , 2014), time-consuming, low quality (Navon & Sacks , 2007), too infrequent to enable prompt control action, potentially unable to facilitate communication of progress information quickly (Fard & Peña-Mora, 2007), non-systematic (Meredith & Mantel Jr. , 2011; Song, Pollalis, & Pena-Mora, 2005), and complex (Kerzner & Kerzner , 2017) (Alizadehsalehi & Yitmen, 2018).

2.3. Automated progress monitoring

Nowadays, each project requires an automated monitoring system that ensures delivery and representation of the most up-to-date design, schedule, cost, and progress performance data in a timely and a comprehensive manner in order to enable control decisions to be made as quickly and easily as possible (Kim , Son , & Kim, 2013). Recent advances in information and communication technologies have enabled researchers to make considerable efforts toward improving the efficiency and quality of project progress control (Bosché, Ahmed, Turkan, Haas, & Haas , 2015; Son , Bosché , & Kim , 2015). These methods and technologies support conventional tasks, ease communications, speed up processes, and manage information efficiently. Automation of project progress control and monitoring process is a great interest to construction industry practitioners since it will aid them in overcoming the limitations associated with presently employed manual data collection and analysis practices (Zhang & Arditi , 2013; Kim , Son, & Kim , 2013). Recently, researchers have attempted to automate the process of construction performance monitoring by leveraging advances in computer vision, robotics, and construction management. Despite recent advances in technologies and equipment for automated progress monitoring, most construction companies worldwide do not utilize them for their projects. This can be due to several reasons, such as the high cost of technologies and equipment, implementation issues, need for skilled staff, and, most importantly, a lack of sufficient information about the impact of automated progress monitoring in comparison with conventional progress monitoring on project performance control (Alizadehsalehi & Yitmen, 2018).

Recent efforts on automating project monitoring have shown the potential for effective construction project control. One of the automations applied to the construction industry is the adoption of Building Information Modelling (BIM). Commercial inspection software packages that use BIM model to facilitate inspection process such as LATISTA, Autodesk BIM 360 Field, Field 3D, xBIM, etc. offer to the inspector the ability to use a mobile device (Tablet PC) instead of paper documents. These software packages are very effective at issues regarding document management, but the inspection process itself has not been automated since the inspector still has to manually navigate around the BIM model while visually inspecting the building. Another survey (Gheisari, Williams , Walker , & Irizarry , 2014) has shown that users prefer a mobile-based augmented reality system for inspection compared to a paper-based one as it is simpler and faster. Although the aforementioned survey was conducted for facility management purposes, it shows that mobile based augmented reality systems for inspection (e.g. BIManywhere) can be also an asset for progress monitoring. However, in that case, an installation and maintenance of QR codes is needed which is inefficient given the dynamic environment of construction projects. Such technologies do not address the subjectivity of reports and the time required for the data analysis, but only facilitate the user to have access to needed information (Kopsida, Brilakis, & Vela, 2015).

Also, some companies are now shifting to automated data acquisition using Global Positioning System (GPS), barcodes, Radio-frequency identification (RFID), video and audio technologies or laser scanners (Navon & Sacks , 2007), for example, used an RFID-based progress monitoring system to track pre-cast structural elements (Sawyer, 2008). However, not all construction elements can be tagged with RFIDs and an additional investment on equipment and human effort is required. Remote controlled web-based cameras are also used for remote monitoring of construction sites (e.g. Oxblue) (Gomez, 2008) but their use is limited to outdoor scenes (Kopsida, Brilakis, & Vela, 2015).

It can be alleged that no current practices offer an automated data analysis to estimate progress status and although there are technologies that can facilitate the visualization of the results of the progress estimation analysis, these technologies have not been yet implemented (Kopsida, Brilakis, & Vela, 2015).

According to Navon and Sacks (Navon & Sacks , 2007), the most economical way to measure performance is to automate the control methods. This entails automation of not only progress assessment but also, as much as possible, planning assignment, resources, project structure for assigning tasks, and responsibilities during all stages of the construction project (Son & Kim , 2010). This double automation would ensures derivation of optimum benefits of using integrated information technology (IT) system. Isaac and Navon (Isaac & Navon, 2014) in 2013 indicated that manually obtained data are required in addition to the automatically collected data. They proposed a frame work for semi-automated project monitoring and control whose ultimate goal was to seamlessly integrate both manually and automatically collected data to improve productivity. Advanced field data capturing technologies that can be used for real-time on-site measurement of performance indicators are rapidly emerging, and their costs are reducing (Alizadehsalehi & Yitmen, 2018).

The research of Alizadehsalehi and Yitmen found that automated project progress monitoring involving an automated approach for recognition of physical progress, accurate and efficient tracking, and analysis and visualization of the as-built (actual) status of buildings under construction—which are critical components of successful project monitoring—is a valuable tool for construction progress monitoring. Site data collection technologies could potentially automate all steps of collecting, analyzing, and representing progress and recognize its deviations from a construction plan. Thus, the present findings contribute to the field of automated project progress monitoring by linking numerous aspects of project progress monitoring and their interrelationships to automated progress tracking and control from stakeholders' perspective. The study analyzed the success criteria (time, cost, and quality) of the projects that benefited from the use of automated progress monitoring. The data obtained from SEM analysis and benefit analysis of the research suggest that automated progress monitoring is an effective framework for improving certain key aspects of the delivery of construction projects and that it directly affects important indicators (time, cost, and quality) of construction projects (2018).

An automated progress monitoring process could be divided into the following steps (a) data acquisition, which refers to sensing technologies that are used for capturing the as-built scenes, (b) information retrieval, which involves the processing for extracting the information needed from the as-built data, (c) progress estimation which includes the comparison between the as-built and as planned model to define the progress status and (d) visualization of the results.

2.3.1. Data acquisition

Radio-frequency Identification (RFID) technologies have been used for inspection purposes in order to retrieve on-site data (Song, Haas, & Caldas, Tracking the Location of Materials on Construction Job Sites. , 2006; Ergen , Akinci, & Sacks , 2007; Kim , Ju, Kim, & Kim , 2009; Grau, Zeng , & Xiao, 2012) and integrate it into a BIM model (Wang, Truijens , Hou , Wang , & Zhou , Building Information Modeling: Onsite construction process controlling for liquefied natural gas industry., 2014). Using this technology, the inspector can automatically retrieve information by scanning the tag using a smartphone or a tablet PC. Although this process facilitates data acquisition of important information and it can work with available commercial BIM-based inspection software, it still requires the installation and maintenance of RFID tags. Additional time and investment is needed and its implementation is difficult in a daily changing construction environment (Kopsida, Brilakis, & Vela, 2015).

Another popular method in automated progress monitoring is to collect as-built data using laser scanning based methods. The acquired data from a laser scanner consists of a point cloud within a 3D coordinate system in which every point is described by x, y and z coordinates. Although, laser scanners offer high accuracy, their use is limited because they are still expensive, they require high cost for maintenance and they need trained users. The discontinuity of spatial data, the needed mixed pixel restoration (Kiziltas, Burcu , Ergen, & Pingbo , 2008), the need for regular sensor calibrations and a slow warm-up time are additional disadvantages (Golparvar-Fard, Peña-Mora, & Savarese, 2012). Moreover, noisy data can be caused by moving machinery and personnel. Also, laser scanners are not easily portable and their resolution decreases as distance increases (Golparvar-Fard, Peña-Mora, & Savarese, 2012). El-Omari & Moselhi (2008) presented a method that combines laser scanning and photogrammetry in an attempt to enhance the speed and accuracy of data retrieval from construction sites. However, merging of the photo images and scanned data needs is carried out by manually selecting common points (Kopsida, Brilakis, & Vela, 2015).

A different way to capture as built data is to use digital images and videos. It is a common method that can provide on-site information by tracking progress, sharing information between people and documenting the different phases of construction. Unlike laser scanners, image based systems are inexpensive and easy to use. Ibrahim & Kaka (2008) present a review of imaging applications in construction and Bohn & Teizer (2010) explore the benefits and challenges of progress monitoring using cameras. Images can be collected in different ways. The camera could be either monocular (Lukin & Trucco , Towards Automated Visual Assessment of Progress in Construction Projects., 2007) or stereo (Son & Kim , 2010). Ibrahim et al. (2009), Zhang et al. (2009), and Rebolj et al. (2008) used a stable camera in a known fixed position and Golparvar-Fard et al. (2009), Leung et al. (2008) and Abeid et al. (2003) suggested the installation of multiple cameras on a construction site. Fixed cameras provide limited views and are prone to occlusions, obstructions and weather conditions. Thus, a comprehensive depiction of progress is not possible. In order to overcome these limitations, in Golparvar-Fard et al. (2011) a number of photos can be taken in and around the construction site (Kopsida, Brilakis, & Vela, 2015).

Videos are also used for capturing spatial characteristics of civil infrastructure in the form of 3D point clouds (Brilakis , Fathi , & Rashidi , Progressive 3D reconstruction of infrastructure with videogrammetry., 2011; Rashidi , Fathi , & Brilakis , 2011). Continuous advancements on cameras and performance processing units enhance the accuracy of the obtained data, reduce the time of processing and increase the potential of using visual data for as-built data acquisition purposes (Kopsida, Brilakis, & Vela, 2015).

Interior environments require different kind of data compared to exterior scenes. Exterior scenes consist mainly of outer columns, beams and walls. However, interior scenes consist of various construction elements (e.g. electrical, plumbing, fire protection etc.) and schedules related to many subcontractors. Many tasks in an interior environment are characterized by changes in surfaces of walls (e.g. painting, tiles, wooden floor, etc.) and mounted objects (e.g. windows, doors, etc.). Some approaches that are used for exterior environments (Bosché, 2010; Lukin & Trucco , 2007; Golparvar-Fard, Peña-Mora, & Savarese , 2012) can also be used for interior environments; however they do not address the aforementioned challenges. Thus, current research activities have not reached an efficient level of treatment of indoor environment challenges (Kopsida, Brilakis, & Vela, 2015).

2.3.2. Information retrieval

Regarding laser-scanning based methods, after the required number of scans, the obtained point cloud has the 3D information that is needed for the comparison between the as-planned 3D model and thus, they do not need much further processing. However, in a point cloud it is difficult to separate objects because the points are unorderly scattered and do not include any object related information. Point cloud processing for object detection purposes requires time and it is computationally expensive (Kopsida, Brilakis, & Vela, 2015).

Regarding images and videos, in the past, data was mainly manually analyzed. However, recently, a number of automated techniques have been presented for analyzing and interpreting image data to retrieve information of the construction as-built scene. The first is photogrammetry. AbdMajid et al. (2004), Memon et al. (2005) and Memon et al. (2006) applied photogrammetry in construction progress monitoring. The authors used photogrammetric techniques to extract 3D models from digital images. A similar application was proposed by Bayrak & Kaka (2004; 2005). Here, the authors used a library that contains a list of elements that make up the 3D model of the building. Although these systems provide useful means of facilitating progress measurement on construction sites, they still require a great deal of human input and same as point clouds, they do not contain object related information (Kopsida, Brilakis, & Vela, 2015).

Other methods for extracting information from visual data use techniques from the areas of image processing and computer vision (Brilakis & Soibelman, 2005). Retrieving data from construction site images which can be incomplete and noisy, is a difficult problem (Trucco & Kaka , 2004). A simple approach that uses computer vision methods, is to compare a sequence of images from a fixed camera and find the differences in the construction process to estimate the progress (Lukin & Trucco , 2007; Ibrahim, Lukins , Zhang , Trucco , & Kaka , 2009). However, these methods have limited success rate and they are not fully automated. Automated detection and identification of building elements according to shape and materials have been proposed using image processing techniques (Brilakis , Soibelman, & Shinagawa , 2005; Zhu & Brilakis, (2010a); (2010b); Zhu, German, & Brilakis, 2010). Texture, color and shape information has been used to classify construction materials such as concrete and steel ((Brilakis & Soibelman , 2008; Zhu, German, & Brilakis, 2010; Zhu & Brilakis, (2010a); (2010b)) and to detect and count the number of bricks on a façade (Hui, Park, & Brilakis, 2014). Window detection (Lee & Nevatia , 2004; Ali , Seifert , Jindal , Paletta , & Paar , 2007) and door detection (Stoeter, Le Mauff, & Papanikolopoulos, 2000; NOZ-SALINAS, Aguirre , García-Silvente, & ALEZ, 2004; Shi & Samarabandu, 2006; Murillo, Košecká, Guerrero, & Sagüés, 2008; Hensler, Blaich, & Bittel , 2010; Yang & Tian, 2010) algorithms have also been developed. Multiple views geometry for retrieving the 3D reconstruction of building structures has also been presented

(Son & Kim , 2010; Golparvar-Fard, Mora , Arboleda, & Lee, 2009; Golparvar-Fard, Bohn, Teizer, Savarese , & Peña-Mora, 2011). However, Golparvar-Fard et al. (2011) and Klein et al. (2012) have shown that the points of the 3D reconstruction are not as accurate as the points obtained by laser scanners. The process of creating a sparse point cloud from images is time-consuming as it can lead up to 7 hours of additional computational time for a single column for image processing (Golparvar-Fard, Bohn, Teizer, Savarese , & Peña-Mora, 2011) (Kopsida, Brilakis, & Vela, 2015).

Although most efforts focus on outdoor environments, several approaches regarding indoor as built data acquisition have also been introduced. Roh et al. (2011) have proposed an interior progress monitoring system that automatically detects construction objects in indoor images. However, this method is not efficient enough since many complexities associated with the interior environment lead to errors. Klein et al. (2012) have tested photogrammetry on indoor images to obtain dimensions of a room. The disadvantages of this method is the manual extraction of dimensions of indoor environment from sparse point clouds using photogrammetry and the need to install visual markers on walls to perform image stitching. Lin & Fang (2013) developed a computer vision based automated inspection system for tile alignment assessment. Whilst the process is highly efficient, the task of tiling is a very specific sub task and as a consequence, this method cannot be generalized for other inspections. In general, object detection in indoor environment is challenging due to the following reasons (Yang , Tian , Yi , & Arditi , 2010): (a) there are many variations of appearance of objects in different interior environments, (b) there are small variations in different object models and (c) most indoor objects lack of texture (Kopsida, Brilakis, & Vela, 2015).

2.3.3. Progress estimation

The as-built information that has been retrieved from the previous step, either using point clouds or images or videos, needs to be compared with the as-planned information in order to assess the current status of progress, decide if the progress is behind, ahead or on schedule and take potential corrective actions. Usually a 4D BIM model (a BIM model including the time schedule of the tasks) is used as an as-planned model and the as-built models are superimposed on the 4D BIM to proceed with the comparison between the two models. The registration process has been performed manually (Memon , Abd.Majid, & et al., 2005; Zhang & Arditi , 2013) (Alizadehsalehi & Yitmen , 2018) or in a semi-automated way (Golparvar-Fard, Bohn, Teizer, Savarese , & Peña-Mora, 2011; Bosché, 2010).

An additional method that requires human interaction for registering the as-built and the as planned model was presented by Roh et al. (2011) where the user has to assign contextual data such as time, location and perspective for each image (Kopsida, Brilakis, & Vela, 2015).

Following the registration, the next step in progress estimation is the recognition of objects and the matching of the as-built object with the corresponding one in the as-planned model (Golparvar-Fard, Peña-Mora, & Savarese, 2012; Bosché, 2010; 2012; Turkan , Asce , Bosché , Haas , & Haas , 2013; Turkan, Bosche , Haas , & Haas , 2012; Rebolj, Podbreznik, & Čuš Babič, 2008) (Zhang & Arditi , 2013). Golparvar-Fard et al. (2012) use voxels and a probabilistic model to detect the progress. On the other hand, Bosché (2010; 2012) and Turkan et al. (2012; 2013) use a surface based recognition metric. The recognized surface is calculated for every object and if that surface exceeds a minimum threshold the object is considered as recognized. Zhang & Arditi (2013) developed a method that counts the number of points in the related portions of the point clouds. Rebolj et al. (2008) have compared a segmented site image and a model using an algorithm that recognizes differences between element features. The views of the model and the site image are assumed to show the same elements in the same perspective. The aforementioned methods could not work for interior environments and tasks such as painting or tiling since they only recognize if an object exists or not in the scene and they cannot perform in real time (Kopsida, Brilakis, & Vela, 2015).

2.3.4. Visualization

As mentioned in the first section, besides efficient on site data collection and timely data analysis, efficient visualization of the progress inspection results is also essential. An efficient way to visualize the progress of a construction project is the use of Augmented Reality (AR). The main problem of Augmented Reality systems is the accurate alignment of computer generated and real world data (Koller , et al., 1997; Azuma R. , A Survey of Augmented Reality, 2007) which depends on the accuracy of tracking the user's viewing orientation and position (Kopsida, Brilakis, & Vela, 2015).

In recent years the interest for Augmented Reality and its applications has increased. Several platforms have been introduced such as AMIRE, ARVIKA, StudierStube, DWARF, DART, etc (Izkara , Pérez , Basogain, & Borro, 2007). Lee & Peña-Mora (2006) and Golparvar-Fard & Peña-Mora (2007) have explored the visualization of construction progress. For progress monitoring purposes the as-planned image from the 3D model and an image from the as-built environment are superimposed. The superimposition leads to a clear visual comparison between what was scheduled and what has been completed. The augmented image can be linked to the schedule to quantify deviations (Lee & Pena-Mora, 2006) (Kopsida, Brilakis, & Vela, 2015).

Different colors can be used for a better visualization of the progress deviations (Lee & Pena-Mora, 2006; Song , Haas, & Caldas , 2006). Golparvar-Fard & Peña-Mora (2007) proposed a semi-automated system for visualizing progress monitoring which aligns the as-planned and as-built views by manually choosing features. However, monitoring interior environments of buildings is difficult using fixed cameras. Using many cameras is also inefficient due to the dynamic environment of the construction site. These problems render interior progress monitoring more challenging. To overcome the aforementioned challenges, Golparvar-Fard et al. (2009; 2010) and Roh et al. (2009) have developed an augmented reality model for visualizing progress status where the user is able to conduct virtual walkthroughs on the construction site and assess progress (Kopsida, Brilakis, & Vela, 2015).

Other AR-based approaches for inspection (Côté, Trudel, Desbiens , Giguère, & Snyder, 2013; Shin & Dunston, 2009; Shin & Dunston, 2010) use large and heavy equipment mounted on tripods at fixed positions. Although these systems lead to accurate positioning, they lack of mobility. Other AR applications use fiducial markers. Wang et al. (2014) used marker-based AR to facilitate onsite information for construction site activities and Kwon et al. (2014) to develop a defect management system for reinforced concrete. These systems require additional time to install the markers in the building. In order to eliminate the use of fiducial markers, Irizarry et al. (2013) introduced Info spot which is a mobile AR system for facility management. It uses three axis gyroscope, accelerometer, Wi-Fi and digital compass hardware. However, the user is constrained to stand in a specific location, the system needs the use of a Wi-Fi network and information has to be assigned to InfoSpots. Additional mobile systems that use AR rely on a combination of Global Positioning System (GPS) (Meža, Turk, & Dolenc, Component based engineering of a mobile BIM-based augmented reality system, 2014) and compasses for position and orientation determination respectively (Woodward, Hakkarainen, & Rainio, 2010). However, these systems suffer from low accuracy and they are unable to be used in indoor environments (Wing , Eklund, & Kellog , 2005) (Kopsida, Brilakis, & Vela, 2015).

Marker-less augmented reality methods have been introduced in computer vision literature that allow alignment of real and virtual objects but they have not yet employed for BIM models (Kopsida, Brilakis, & Vela, 2015).

2.4.5. Synthesis

Brilakis, Kopsida and Vela introduced a rating system using color where white means good performance, grey means mediocre performance and green means poor performance. The rating system for each of the criteria is illustrated in Table 1. For each of the rating a brief explanation is presented as depicted in Table 2. Numeric data is given where applicable. The rest are qualitatively assessed. (Kopsida, Brilakis, & Vela, 2015)

Table 1, Rating system of criteria (Kopsida, Brilakis, & Vela, 2015)

Method	Good performance	Medicore Performance	Poor performance
Utility	General occasion solution	General occasion solution but with some limitations	Limited occasions
Time effiency	Instant information retrieval	< 1h	> 1h
Accuracy	Precision in all steps	Only some steps of the process are automated	None
Level of automation	Every step is automated		None
Required Preparation	None	< 1h	> 1h
Training requirements	None	Need for training, easy to to learn	Specialised personnel
Cost	< €3500,-	€3500,- - €11.500,-	> €11.500,-
Mobility	Handheld equipment	Large equipment	Large and heavy equipment

Table 2, Performance of solutions (Kopsida, Brilakis, & Vela, 2015)

	Mobile AR	Stationary AR	RFID	Laser Scanners	Vision Static Image	Vision Based Reconstruction	Ideal Case
Utility	multiple occasions	multiple occasions	multiple occasions	only spatial data	limited applications	only spatial data	multiple occasions
Time efficiency	time spent on manual navigation of BIM	time spent of manual registration within registered view	instant information retrieval	time needed for scans	time spent on assigning manual information	time spent on the reconstruction	automatic information retrieval and assignment
Accuracy	AR registration, errors, subjective evaluation of progress	accurate AR registration, subjective evaluation of progress	subjective evaluation of progress	accurate	simple tasks	variable results, and spatial data	accurate
Level of automation	automated document management and data acquisition, no data analysis	automated document management and data acquisition, no data analysis	automated document management and data acquisition, no data analysis	automated document management and automated data analysis	partially automated data acquisition automated data analysis	partially automated data acquisition, automated data analysis	fully automated
Required preparation	minimal set-up required	set the equipment (< 1h)	installation and maintenance of tags (> 1h)	set the equipment (< 1h)	minimal set-up required	minimal set-up required	minimum
Training requiements	none	none	none	trained personnel for using the scanner	none	trained personnel for the reconstruction	none
Cost	consumer hardware	tracking cameras (€11.500,-)		laser scanner (€35.000,-)	consumer hardware	consumer hardware	operates on commercial hardware
Mobility	handheld equipment	large equipment on tripod	handheld equipment	large and heavy equipment	handheld equipment	handheld equipment	handheld equipment

The best solution is, as can be seen in the table 2, mobile AR.

2.4.6. Sub-conclusion concerning automated monitoring

Brilakis, Kopsida and Vela concluded (see table 2) that Mobile AR systems meet more of the requirements compared to the other proposed methods. They are cheap and easy to use in every environment but the systems that have been proposed so far by researchers and presented in the literature review, use either markers which require additional time and cost for installation and maintenance; or Geospots that limit user's location, need preprocessing and need the use of a WiFi network, or they do not perform in real time. Model-based augmented reality algorithms have been developed that could be used for the registration between the as-planned and as-built model, however, their performance within the constraints required of efficient real-time operation on a construction site has not been explored. In addition to this, the presented mobile AR systems do not perform any data processing for progress estimation purposes (Kopsida, Brilakis, & Vela, 2015).

Also Meža, Turk and Dolenc compared the understandability and usability of project documentation using the following techniques: (1) 2D plans, (2) BIM ona PC, (3) the use of tablet computers and (4) augmented reality. The techniques were compared with each other and quantitatively evaluated in the two use cases: (1) the visualization of preliminary design and (2) the monitoring of construction progress. The comparison showed that augmented reality is at least one grade better than any other presentation technique. The cumulative of responses showed that the 3D mode is approximately 7% better than 2D, while AR could improve 3D up to 20%; however, only when taking into ac-count certain assumptions (Meža, Turk, & Dolenc, 2015).

Although the data capturing technologies for project monitoring, approaches like BIM, and different novel software and programming tools are widely available, most construction companies worldwide do not utilize them for their projects. This can be due to several reasons, such as the high cost of technologies and equipment, implementation issues, need for skilled staff, and, most importantly, a lack of sufficient information about the impact of automated progress monitoring in comparison with conventional progress monitoring on project performance control. There is still a need to further develop the technologies, software, and algorithms and determine all the factors that affect the use of AR in the construction industry.

2.4. Augmented reality

While the design phase is largely digitized and increasingly integrated around BIM, for a complete digitalization of the construction industry, structured information models would need to be available on construction sites where the information is used to shape a material world. However, on the construction site the IT infrastructure is not readily available. Things began to change with the introduction of mobile computing (Rebolj & Menzel, 2004) and the field is still evolving (Meža, Turk, & Dolenc, 2015).

The outputs of construction information processes (designs, plans and schedules) provide the control information for the material processes in construction (Turk , et al., 1997). The media to bring the information from the digital models to construction site where it is used to shape physical reality are still 2D documents such as floor plans, cross sections, sketches, etc. The construction site is integrated into the construction process using media and formats that pre-date computers. Situating information and establishing the relation between the real-world of the construction site and design information remains the task of humans. In this task they are not assisted much by technology. Relevant information from the model has to be extracted, based on the user's role in the project, location and time. The graphical representation of this information in 2D must be situated and contextualized with the physical 3D reality for which people rely on their spatial awareness. It is the technologically largely unassisted human mind that is bridging the gap between the real world of the construction site and the virtual world of the information model and is integrating the two. This is what engineers on site have been doing since the introduction of drawn design information centuries ago. The problem at hand is how to assist this process with technology (Meža, Turk, & Dolenc, 2015).

Although virtual and real environments are two completely different entities it is practically impossible to make a clear boundary between them. They can be better presented with two poles of continuum (Milgram & Takemura, 1994), the real and the virtual. The virtual environment must be completely predefined since computers cannot make their own assumptions (Huggins , 1994). The real is a complex mixture of natural events and items that exist in one of the pole of the continuum. Reality, therefore, includes all that can be created, built, planned, observed, understood etc (Meža, Turk, & Dolenc, 2015).

The other extreme of that continuum is a virtual environment, which allows engineers and designers to design objects in imagined, virtual, and designed, but not yet materialized world. Augmented reality is therefore the middle segment of continuum where virtual elements are added to real world (Azuma R. , 1997).

2.4.1. Intersection between conscious real and virtual

The role of augmented reality can theoretically be explained in the context of the meaning triangle in Figure 3 (Meza , Turk, & Dolenc, 2013). The concept is an idea in the mind that refers to that specific referent (real world object). The symbol is a visual or audible signal symbolizing the idea about that referent.

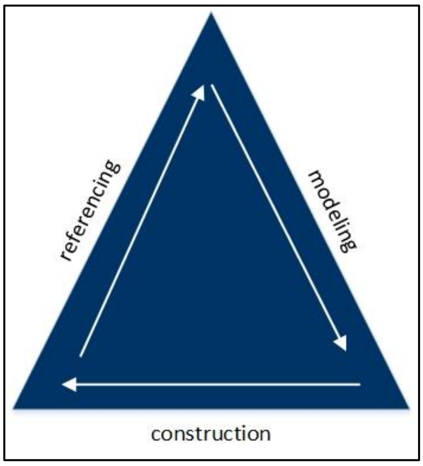

Figure 3, The meaning triangle (Meza , Turk, & Dolenc, 2013)

The presented example shows that it is possible to stablish a direct relation between referent-reference and reference-symbol (Figure 3). The first is called referencing and the second modelling. The relation between the symbol and the object is more complicated as both exist outside the mind of the human. However, one could say that construction is a process in which symbolic design representations (SYMBOL) are translated into real world buildings (OBJECT).Unless robots do this, human interpretation of symbols is essential. Augmented reality assists in this interpretation because it places the symbols over the picture of the real world. It is a superior technology to 2D plans and projections and virtual reality because these technologies keep the symbolic and the real apart with the human mind acting as the interface between the two (Meža, Turk, & Dolenc, 2015).

2.4.2. Opportunities/functionalities

Scheduling:
Augmented reality will improve the scheduling aspect of the construction industry greatly; it can show an as-planned vs. an as-built structure to allow visualization of progress (Zollmann, et al., 2014). In a survey of architects and engineers that was conducted by Meža et al. about construction progress monitoring, the results favored the augmented reality on a tablet PC to other 3D models or a Gantt chart (Meža, Turk, & Dolenc, 2015). Based on other questions in the survey, one thing Meža et al. were able to conclude is that it is possible to see and estimate the work that is done on site is in accordance with the proposed schedule of the job (Meža, Turk, & Dolenc, 2015). Wang et al. also mentioned using augmented reality for project progress monitoring as a way to compare the project progress to the schedule (Park, Lee, Kwon, & Wang , 2013). Wang takes monitoring a step further

and connects augmented reality to material tracking to ensure that the necessary materials are on site (Park, Lee, Kwon, & Wang , 2013). As projects become more complex many scholars and researchers are looking to augmented reality to resolve the complexity of projects (Lin, Liu , Tsai , & Kang , 2014). Many researchers like Mani Golparvar-Fard have researched programs D4AR and how it is used to monitor progress on job sites (Golparvar-Fard, Peña-Mora, & Savarese, 2009). Although there are many uses for augmented reality in construction, progress tracking is one of the most used functions of augmented reality today (Omar & Nehdi , 2016). Another function that Omar and Nedhi mention augmented reality can be used for communication (Omar & Nehdi , 2016) (Behzadi, 2016).

Communication/Information Retrieval:
In the construction industry, communication and information retrieval are two important keys to the success of all projects (Lin, Liu , Tsai , & Kang , 2014). Access to project information on-site is significantly improving with the introduction of different augmented reality (AR) programs compared to more traditional information sources (Pejoska , Bauters, Purma , & Leinonen, 2016). These AR systems allow fast access to information helps project managers to decide on corrective actions to minimize cost and delays due to performance discrepancies (Bae , Golparvar-Fard, & White , 2013). To reduce the difficulties for on-site information retrieval many companies are starting to develop lightweight mobile devices. These companies are working to develop devices that could project construction drawings and related information based on the location of the user (Yeh , Tsai, & Kang, 2012). Also researchers are developing programs that work with a mobile device's camera to help identify location and orientation of field based solely on a site photograph (Bae , Golparvar-Fard, & White , 2013). These new AR programs allow multiple parties associated with a construction projects the ability to clearly grasp the whole picture of the project site and to make accurate predictions about future activities (Lin, Liu , Tsai , & Kang , 2014). The added visualization benefits of AR technologies allow for better communication between parties when commenting and making suggestions for a particular project (Hsieh, Kang, & Lin, 2016). There are however a few barriers to the adoption, "immature core virtual reality technology, conservative nature of construction businesses and size of building information models" (Meža, Turk, & Dolenc, 2015) AR is still relatively its early stages of development pertaining to the construction industry but it is already showing great potential.

Man-labor Hours:
In the construction industry, time and efficiency are key to a successful project. As the world evolves there is a constant push for innovation in all aspects of life. This is no exception in the construction industry. As new technologies emerge the construction process is becoming more and more streamlined due to new technologies and innovation. These innovations solve problems including lack of manpower in the management, and cost efficiencies within the construction project. These innovations include augmented reality and virtual reality technologies. Augmented reality, which is a new and emerging technology in construction, is deemed to be a key enabler to address the current shortcomings of BIM on-site use in construction (Wang, et al., 2013). These technologies allow construction management to address defects that might be overlooked in the inspection process and save time doing so. If managers know the core control time points and measures for works to be checked proactively through the defect domain ontology, then the worker's performance can be automatically checked at the right time with BIM and AR applied inspection tools without visiting the workplace (Park, Lee, Kwon, & Wang , 2013). This allows managers to save both time and money on specific projects while lowering Man-Labor hours and cost efficiencies due to defects and construction rework. Much money and time are wasted because plans or drawings are misinterpreted, or the information is transferred imprecisely from the plan to the real object (Wang , Truijens, Hou, Wang, & Zhou , 2014). By implementing AR technologies managers are much more time oriented to their project. If managers know the core control time points and measures for works to be checked proactively through the defect domain ontology, then the worker's

performance can be automatically checked at the right time with BIM and AR applied inspection tools without visiting the workplace (Park, Lee, Kwon, & Wang , 2013). Another benefit of AR is that this technology allows for a better understanding of what work is actually going on, and what it should look like when it is completed. AR was regarded as a way to bring notable additional value and sense of concreteness especially in close-to-target locations where the shapes and volume of the planned buildings could be visualized. (Olsson , Savisalo, Hakkarainen, & Woodward, 2012). In other words, the reduction of time due to switching treatment implies that AR facilitates an assembler's understanding of the assembly process. (Hou, Wang, & Truijens , 2013).

Safety:
In the construction industry, just as any other field of work, safety needs to be the top priority to everyone associated with our field of work. No other industry promotes and encourages safety as the construction industry. Unfortunately, there are still too many accidents in this industry. (Albert, Hallowel, Kleiner , Chen , & Golparvar-Fard, 2014). A lot of companies invest a tremendous amount of money into safety programs and trainings. By using augmented reality, the total cost of "the same knowledge that needs to be imparted with respect to safety, could be reduced dramatically" (Agrawal , Acharya , Balasubramanian, Agrawa, & Chaturvedi, 2016). The total cost of using augmented reality is cheaper because the equipment used could vary from high end gear to a simple smartphone. A smartphone could be use because of the infinite possibilities that applications provide. "Augmented reality applications are cheaper and more efficient ways to enhance human safety" (Agrawal , Acharya , Balasubramanian, Agrawa, & Chaturvedi, 2016). These applications could run various drills, or specific scenarios that will give the user a real life feeling of a potential hazard. Various authors also state that progress monitoring are not systematically monitored well, making jobsites prone to potential risks (Golparvar-Fard, Peña-Mora, & Savarese, 2009). In addition, the authors explain how the use of augmented and virtual reality on cranes will provide a safer method of locating and selecting the appropriate cranes for different projects (Golparvar-Fard, Peña-Mora, & Savarese, 2009). A different approach for using augmented and virtual realities is how they could improve safety by obtaining better training. A research illustrates, for example, how the usage of augmented reality proves the best training in the shortest time, while also retaining the longest knowledge and skill acquired through the simulator (Akyeampong, Udoka, & Park, 2012). There are also other types of trainings; one in which focuses on better decision making by using simulated technology such as augmented and virtual will dramatically improve to have safer decisions (Attia , Gratia, Herde, & Hensen , 2012; Behzadan & Kamat , Interactive augmented reality visualization for improved damage prevention and maintenance of underground infrastructure, 2009). These type of technologies will only improve the quality of work of the person who underwent training using augmented and virtual reality, ultimately reducing the probability of accidents.

2.4.3. Integration

AR, BIM and Lean Construction
Little to no information was found in the literature regarding the integration of AR, BIM and Lean Construction. This was mainly because the development of this technology, and how it can be implemented to projects is still being researched. In both publications, the use of these new techniques for visualization is proposed for some stages of the workflow, as it is the design and construction stage, and it is being analyzed to determine its impact in the automation and shortening of the processes (Gurevich & Sacks , 2014; Dave , Koskela , Kiviniemi , Owen , & Tzortzopoulos, 2013) (Calderon-Hernandez & Brioso, 2018).

Some Lean specialists are developing systems with BIM software in 4D, 5D, 6D, and other technologies (Seppänen, Modrich, & Ballard, 2015) and it is likely that AR will be compatible with these new platforms. The attempt is to work in close relation with the users of the construction industry to try to integrate the technology with the workflow that the Lean Construction philosophy proposes and make them shorter, faster and friendlier (Calderon-Hernandez & Brioso, 2018).

AR and BIM

The AR tool is being studied for both the design and construction phase. Since the design phase is characterized by being a dynamic process with several iterations, AR can be implemented in this stage during collaborative meetings for decision making to navigate through the design options (Hyeon-Seung, So-Yong, Hyoun-Seok, & Leen-Seok, 2013). As for applying AR during the construction stage, the usefulness of the BIM of the project can be increased. The purpose of this application is to reduce the time in the schedule, minimize costs and ensure the quality of the product through an improvement in the constructive process. This way, the adopted process can be visualized and at the same time a risk analysis can be done to mitigate it beforehand (Hyeon-Seung, So-Yong, Hyoun-Seok, & Leen-Seok, 2013) (Calderon-Hernandez & Brioso, 2018).

It's, for example, possible to use AR in 4D to make a comparison between what is being executed and what was programmed in real time (Han & Golparvar-Fard , 2014). The automatization of progress monitoring is important since early detection of a fallout in schedule represents an opportunity to decrease the impacts (Han & Golparvar-Fard , 2014). On the other hand, senior researchers are developing integration proposals of techniques of low cost like the use of BIM software in 4D, 5D, drone's systems and the Augmented Reality technique (Ballard , 2008), (Irizarry, Gheisari, & Williams, 2013) (Calderon-Hernandez & Brioso, 2018).

Since most of the research conducted in the field of AR, addresses the technology involving this application, the classification of this literature is based on it. For a better understanding of the current state of the art of Augmented Reality, the documents were classified based on the phase of the project that was studied (design phase, construction phase or both), the limitations the research presented (social acceptance from the AEC professionals, registration problems, ergonomics of the devices available for display, data intake, occlusion issues, alignment between real and virtual entities, connectivity and the capability of the devices for processing information) and the future work that was proposed (wearable devices, progress monitoring in the construction phase, implementation, localization speed, including remote servers and improving visualization). Figure 4, illustrates how most of the research has been conducted towards the construction phase of the project (Calderon-Hernandez & Brioso, 2018).

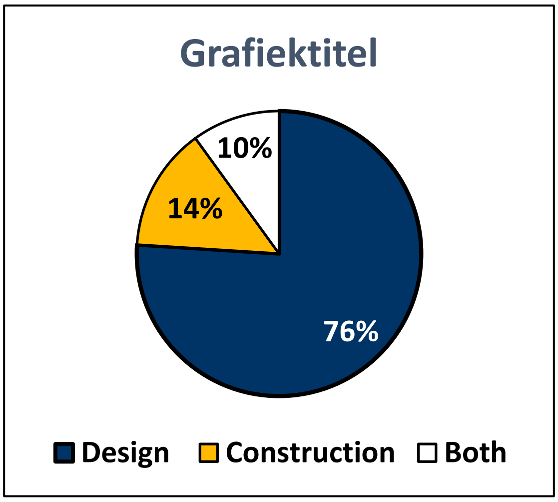

Figure 4, AR and BIM research in the project phase (Calderon-Hernandez & Brioso, 2018)

The AR application has been studied mainly for monitoring, inspection, training and as-built data intake. As for the design phase of the project, even though it has the greatest potential to increase quality and reduce cost in the long term (Krakhofer & Kaftan, 2015), it has not been addressed as exhaustively (Ahmed , 2018) (Calderon-Hernandez & Brioso, 2018).

This application still faces several challenges, one of them is to determine the position of the user and to align the virtual data with the real data correctly (Meža, Turk, & Dolenc, 2015). This depends on how precisely the position and visual orientation of the user is determined (Kopsida, Brilakis, & Vela, 2015). As any automated process, the importance of its implementation lies in the time, effort and cost savings it represents, as well as that the information generated allows the detection of discrepancies and the implementation of corrective actions. The main limitations found are described in Figure 5, being hardware capabilities and occlusion issues the main ones. The occlusion problem seems to be solved with depth buffering testing, which allows the invisible part of a virtual object to be correctly occluded (Behzadan, Dong , & Kamat, 2015) (Calderon-Hernandez & Brioso, 2018).

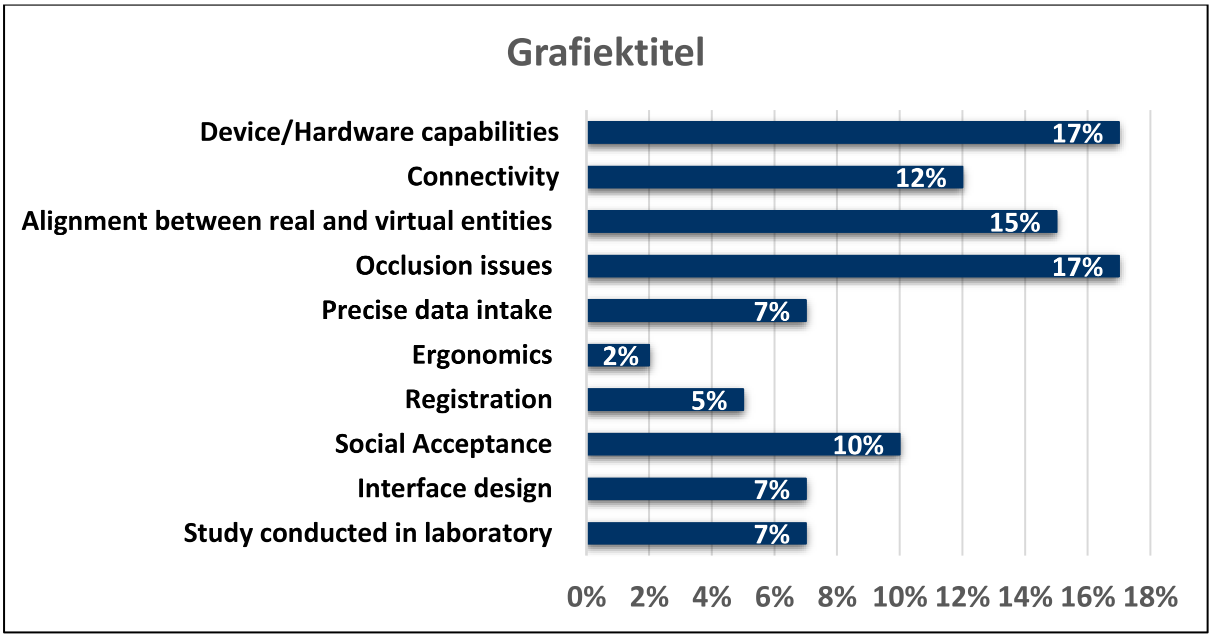

Figure 5, Limitations/Challenges in AR-BIM (Calderon-Hernandez & Brioso, 2018)

Future research work proposed involves implementing and testing the systems in a real construction environment, automatization of the data intake for construction progress and developing devices that are safe and wearable onsite. Figure 6 shows what future research is going to be leaning towards. It is also very important to investigate a method to help the construction industry accept and adopt AR technology by realizing the benefits it includes (Alsafouri, Ayer, & Tang, 2015) (Calderon-Hernandez & Brioso, 2018).

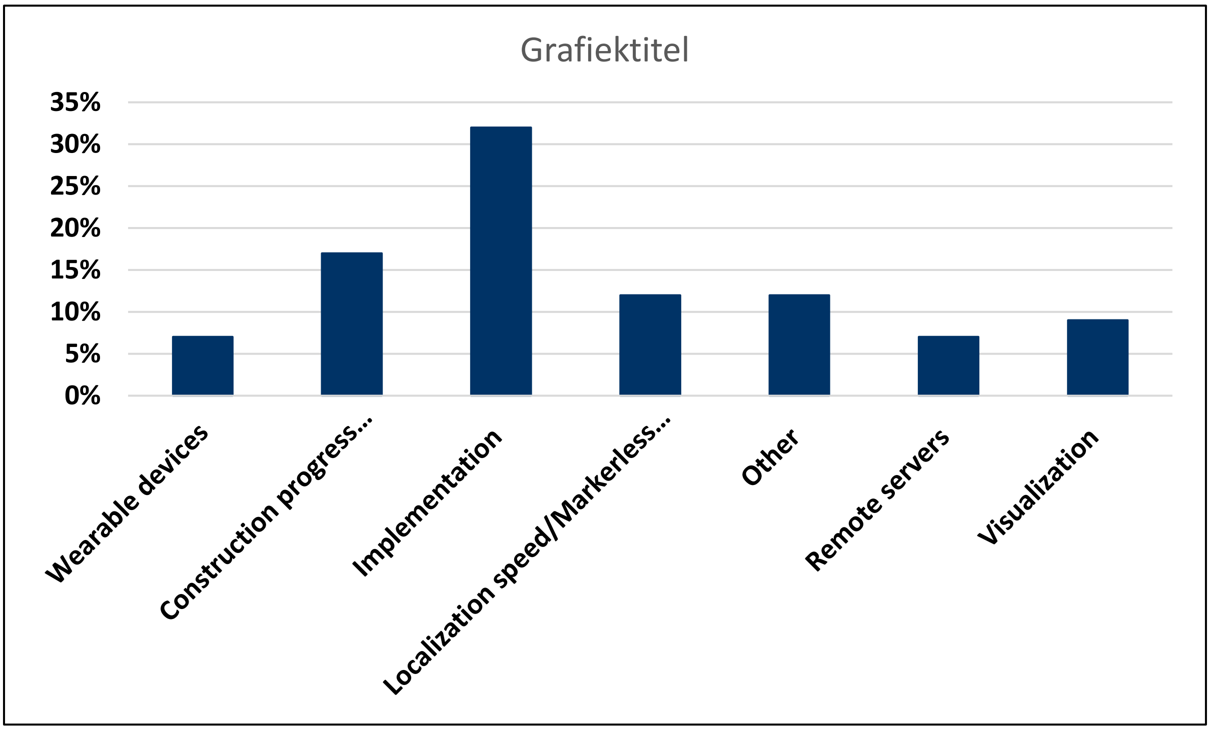

Figure 6, Future work proposed for AR and BIM (Calderon-Hernandez & Brioso, 2018)

In the future, it is expected that the limitations of the AR technology are solved by IT professionals and software and hardware developers (Calderon-Hernandez & Brioso, 2018).

2.4.4. Obstructions to the implementation AR

Cost of AR technology
Being a relatively new concept, the initial costs of setting up an AR system in place can increase the costs of the projects (Agarwal, 2016). An increased cost would cause a negative acceptance among the decision makers of the project. (Silverio, Renukappa, & Sures, 2017)

Hardware issues
The main goal of AR applications is to overlay virtual information on top of real world objects. AR applications need to create the perception that simulates that virtual and real entities coexist in the same space with an adequate spatial alignment of real and virtual entities, without proper registration, this perception is compromised (Agarwal, 2016).

Size and weight represented another important issue to consider (Azuma , et al., 2001). Nowadays Smart devices allow users to implement AR-based applications with mobility. Others, head mounted displays like the Daqri Smart helmet and HoloLens are aiming to provide a mobile solution for the manufacturing and construction industry (Greenhalgh , Mullins , Grunnet-Jespen , & Bhowink , 2016). (Silverio, Renukappa, & Sures, 2017)

Development of applications
The development of user-friendly applications that abide to the right paradigm of context awareness and pervasiveness is an important barrier for implementing pervasive AR solutions. With the field of AR being very vast and diverse companies need to consider developing applications specifically for the construction industry. (Silverio, Renukappa, & Sures, 2017)

2.4.5. Drivers

Error and cost reduction
The most significant advantage that this technology provides to the user is the reduction of errors that may take place during the construction proves. By providing a virtual design on the field, it becomes easier to control the different processes and achieve a better output (Agarwal, 2016). Since error rectification reduces, the cost of material and workforce utilized for that rectification is reduced, that helps in reducing the overall overheads of a project (Agarwal, 2016). (Silverio, Renukappa, & Sures, 2017)

Continued assistance
Pervasive AR is all about continuity instead of isolated tasks, this means that all the possible applications of this technologies should be integrated into a personalized single device or system which provides continued assistance to the user (Grubert , Kranz, & Quigley , 2015). (Silverio, Renukappa, & Sures, 2017)

2.4.6. Possible application of AR

Design
Spatial models can help the designer identify the flaws and rectify them at the design stage itself. Also, it can contribute to create innovative designs as the architect can see the structure in real time,

which can help in various advantageous changes (Agarwal , 2016). (Silverio, Renukappa, & Sures, 2017)

Visualization of drawings and technical information onto the job site
The translation of drawings into a structure is not an easy task. It involves various steps of identification of different structural elements and subsequently constructing them. Since the project is envisaged in phases, it may so happen that errors might creep in during various stages (Agarwal, 2016) . The visualization of drawings into 3D structures requires the integration of AR with other technologies such as BIM, to enable context aware solutions based on 3D information. One example is the utilization of AR to display the positioning and layout of underground infrastructure and to mitigate undesired damages (Schall, et al., 2009). (Silverio, Renukappa, & Sures, 2017)

Marketing
Explaining a project to a person without a technical background is a problem that all projects have to face. Architectural drawings may be extraordinary, but they are still on a smaller scale and generally 2-D. Using the concept of AR, the client can be given a virtual tour of the project, with all the colors and the different views that can be observed for the project. This can lead to better marketing strategies for organizations (Agarwal, 2016). (Silverio, Renukappa, & Sures, 2017)

2.4.7. Sub-conclusions Augmented Reality

According to Calderon-Hermandez and Brioso, a very limited amount of evidence was found on the integration of Lean Construction with BIM and AR in terms of the automatization of the workflow proposed by Koskela. It could be suggested that AR is an extension or a supplement of BIM. Also, these applications have a lot of potential during the design and construction stages of a project and its integrated use must be researched on a deeper level. The flow processes must be designed, controlled and/or improved in an orderly manner, generating activities with added value and reduction of waste. Future work must involve an integration proposal of AR, BIM and Lean Construction (Calderon-Hernandez & Brioso, 2018).

The research of Meža, Turk and Dolenc concluded that although augmented reality has a substantial potential it is unlikely that in the nearby future it could replace the conventional presentation techniques. The main barriers were found to be (a) GPS positioning in general and indoors positioning in particular, (b) visual occlusion, and (c) scalability in relation to the size of BIM models and end-user experience (frame-rates of virtual elements updates, general responsiveness, etc.). Some of the barriers could be removed by developing a specialized AR system with features like remote server side distributed near real-time video and image processing, advanced computer vision algorithms to help with unwanted visual occlusions, etc (Meža, Turk, & Dolenc, 2015).

The idea of using augmented reality needs to be developed in parallel with conventional methods, so that when the basic technology for augmented reality matures engineers and architects will be able to take advantage of it. Needless to say, well-formed digital models, such as BIM, are a prerequisite for AR as well (Meža, Turk, & Dolenc, 2015).

Augmented technology is a supplement of virtual technology, giving users a real time view of what is occurring before them. Although augmented technology has only been around for just over 50 years, it has seen its‟ greatest improvements and an increase in demand in the last 20 years. It is clear from the research reviewed that these great improvements in augmented technology are having an effect on the industry in multiple ways. For example, when trying to get a picture of how a final project will look during different stages in the construction process. Along with this, it is also clear that augmented technology can greatly improve the effectiveness of safety training, because it allows people to get a real time view of different situations on the job site. Even though augmented technology appears to be an important tool in the construction industry, there are multiple drawbacks of such technology. However, these drawbacks and barriers are soon broken by the upcoming generations and the constant advancement in technology around the world. Assuming that augmented technology will only improve with time, it is almost certain that such technology will play a critical role in construction for years to come (Behzadi, 2016).

Literature show field workers and project managers have high interests in using non-immersive and desk-top standalone (individual) AR technologies during construction phase of a project to compare as-planned versus as-built statuses to monitor progress and defect detection. Whereas, it is predicted that future trend, is more toward using collaborative and internet based mobile AR systems which have applications not only in construction phase, but also in procurement and maintenance phases of a project. Due to various benefits of AR technology for construction industry, the application of AR systems for initiation and procurement phase of a project to compare model vs. model and reality vs. reality is recommended. Moreover, lightweight mobile and immersive AR systems are also recommended for field personnel due to dynamic environment of construction fields. Currently, most of the AR systems found in the literature are trial/demonstration, hence they are developed for specific purposes they do not have all of the above criteria, however some new systems offers some valuable feature and may provide a competitive advantages. (Rankohi & Lloyd, 2013)

2.5. Big Data and AR

The ability to process large amounts of data and to extract useful insights from data has revolutionized society. This phenomenon—dubbed as Big Data—has applications for a wide assortment of industries, including the construction industry. The construction industry already deals with large volumes of heterogeneous data; which is expected to increase exponentially as technologies such as sensor networks and the Internet of Things are commoditized. In this paper, we present a detailed survey of the literature, investigating the application of Big Data techniques in the construction industry (Bilal M. , et al., 2016).

Using latest imaging technology, the progress of the on-going construction is captured at the real time. Big Data Analytics will process the real-time streams of these images to measure the daily change and updated the BIM models and construction schedule accordingly. The project managers are presented with an update to date progress on the schedule, which will, in turn, enable them to see whether they are lagging behind on the project or still follow the schedule. Accordingly, the project managers can proactively respond in case of any delay is reported. This will save them a lot of money due to penalty whenever the deadline is missed, and improve the overall project monitoring and control. This is also aligned with the vision of BIM adoption. In this way, Big Data can help the industry to deliver the projects on time (Bilal M. , et al., 2016).

2.5.1. Big Data with Augmented Reality

Rankohi et al. (Rankohi & Waugh, 2013) argued that visualization and simulation aspects of the construction industry apps can be revamped with AR to enhance their usability. Some of the exciting AR application areas are highlighted such as virtual site visits, proactive schedule dispute identification and resolution, and as-planned vs. as-built comparison. Chi et al. (Chi, Kan, & Wang, 2013) pointed out the following four pillars for wider AR adoption in the construction industry. (i) Localisation, the ability to accurately impose virtual object on the real-life scene. (ii) A natural user interface, which provides easy and intuitive user experiences to increase the usability of AP software. (iii) Cloud computing, which enables apps to store and retrieve information seamlessly everywhere, and (iv) mobile devices, which are getting smaller, cheaper, and powerful and play a vital role in AR environment (Bilal M. , et al., 2016).

William et al. (Williams, Gheisari, Chen, & Irizarry, 2014) went ahead by bringing BIM, mobile technology and AR together. The BIM aspects of geometry translation, indoor localization, attribute assignment, and registration are explored for integration with mobile AR. The study proposed BIM2MAR, which provides general guidelines for integrating BIM with mobile AR. It is emphasized robust BIM integration requires new approaches for BIM geometry conversion and indoor localization of BIM using geo-coordinates. Jiao et al. (Jiao , Zhang, Li, Wang, & Yang, 2013) developed a web3D-based AR environment to integrate BIM, business social networking services (BSNS), and cloud services.

AR and Big Data inevitably converge. The complexity associated with Big Data in construction is enormous, which can only be surmounted by advanced methods of visualization, particularly Augment and Virtual reality technologies. This requires new interactive platforms and methodologies to visualize construction related datasets. The aim is to comprehend better and interpret the complicated structures and interconnection buried inside the Big BIM Data for design exploration and optimization (Bilal M. , et al., 2016).

Currently, BIM is prevalent in the design world, with very limited utilization across the construction and FM stages of the building. The real intent of BIM could never be achieved until it is employed in every stage of the building lifecycle. At present, no such mechanism can facilitate the tracking of progress of various construction sites using automated tools. It is indeed labor-intensive as well impractical (to some extent) to update the BIM model with such minute details pertaining to the daily construction progress (Bilal M. , et al., 2016).

Employing Big Data and sensing technologies could move the state of the art in domain of construction progress monitoring to the next level. Using latest imaging technology, the progress of the on-going construction is captured at the real time. Big Data Analytics will process the real-time streams of these images to measure the daily change and updated the BIM models and construction schedule accordingly. The project managers are presented with an update to date progress on the schedule, which will, in turn, enable them to see whether they are lagging behind on the project or still follow the schedule. Accordingly, the project managers can proactively respond in case of any delay is reported. This will save them a lot of money due to penalty whenever the deadline is missed, and improve the overall project monitoring and control. This is also aligned with the vision of BIM adoption. In this way, Big Data can help the industry to deliver the projects on time (Bilal M. , et al., 2016).

2.5.2. Pitfalls of Big Data in combination with AR

Cost implications for Big Data in the construction industry

Every technology incurs cost so introducing Big Data in construction is not for free of charge. Companies are required to set up data centers, or instead (a more modern approach) make use of cloud services, and purchase software licenses, which can be an attractive investment. Also, skilled IT personnel to keep the entire ecosystem running is another overhead. So Big Data has inevitably substantial cost implication. The construction business is considered amongst the low-profit-margin businesses, and introducing such costly add-ons to projects are more likely to be opposed and difficult to be defended. However, Big Data has the potential to enhance the overall project delivery by optimizing processes and reducing risks that companies usually bear due to myriad inefficiencies such as delays, litigations, etc. It is highly optimistic that construction industry can gain huge revenue from this investment as experienced by other industries, provided the right methodology is used to employ Big Data. The exact cost implication of Big Data is, however, difficult to quantify. More studies on cost benefit analysis of using Big Data technologies in construction projects are required (Bilal M. , et al., 2016).

Internet connectivity for Big Data applications
To monitor project site activities at real-time, instant data transmission between project sites (dams, highways, etc.) and centralized Big Data repository should be supported. However, project sites usually have low bandwidth; due to unavailability of sophisticated networking infrastructure in rural, underdeveloped areas. Advanced wireless sensor networks need to be extended to tackle internet connectivity issues in these types of Big Data applications; otherwise, the decisions on stale offline data will not be useful for effective monitoring (Bilal M. , et al., 2016).

2.5.3. Sub-conclusions Big Data and AR

The research of Maaz, Bandi and Amirudin suggests that there are plenty of room for big data research from the construction industry perspective. The limited big data research shows both academics and industry expert shall work hand in hand to have an agreed direction, interest and solutions for the construction industry to advance towards realizing the big data dream.

Although the construction industry generates massive amounts of data throughout the life cycle of a building, the adoption of Big Data technology in this industry lags the progress made in other fields. With the commoditization of the technology necessary for storing, computing, processing, analyzing, and visualizing Big Data, there is immense interest in leveraging such technologies for improving the efficiency of construction processes (Bilal M. , et al., 2016).

Bilal et al. concluded that while data-driven analytics have long been used in the construction industry due to the broad applicability of such techniques in many construction subdomains, the adoption of the recent, much agiler and powerful, Big Data technology has been relatively slow. Although Big Data trend is gradually creeping in the industry; its applicability is amplified further by many other emerging trends such as BIM, IOT, cloud computing, smart buildings, and augmented reality (Bilal M. , et al., 2016).

2.6. Conclusions literature research

Using the literature three sub-questions could be answered.

Sub question 1 → What is the current state of AR in the construction industry?

There are many uses for AR in the construction industry, whereof progress tracking is one of the most used functions. As projects become more complex many scholars and researchers are looking to augmented reality to resolve the complexity of projects (Lin, Liu , Tsai , & Kang , 2014). Many researchers like Mani Golparvar-Fard have researched programs D4AR and how it is used to monitor progress on job sites (Golparvar-Fard, Peña-Mora, & Savarese, 2009).

Access to project information on-site is significantly improving with the introduction of different augmented reality (AR) programs compared to more traditional information sources (Pejoska , Bauters, Purma , & Leinonen, 2016). To reduce the difficulties for on-site information retrieval many companies are starting to develop lightweight mobile devices.

AR is deemed to be a key enabler to address the current shortcomings of BIM on-site use in construction (Wang, et al., 2013). These technologies allow construction management to address defects that might be overlooked in the inspection process and save time doing so. If managers know the core control time points and measures for works to be checked proactively through the defect domain ontology, then the worker's performance can be automatically checked at the right time with BIM and AR applied inspection tools without visiting the workplace (Park, Lee, Kwon, & Wang , 2013).

A different approach for using augmented and virtual realities is how they could improve safety by obtaining better training. A research illustrates, for example, how the usage of augmented reality proves the best training in the shortest time, while also retaining the longest knowledge and skill acquired through the simulator (Akyeampong, Udoka, & Park, 2012).

There are however a few barriers to the adoption, for example: immature core virtual reality technology, conservative nature of construction businesses and size of building information models" (Meža, Turk, & Dolenc, 2015) AR is still relatively its early stages of development pertaining to the construction industry but it is already showing great potential (Behzadi, 2016).

Alsafouri, Ayer, & Tang emphasize the importance of investigating a method to help the construction industry accept and adopt AR technology by realizing the benefits it includes (Alsafouri, Ayer, & Tang, 2015; Calderon-Hernandez & Brioso, 2018). Further, the aspect of 'implementation' scores the highest concerning proposed future work on AR. This emphasizes the urgency to establish the current obstructions and enablers concerning the implementation of AR, in order to outline the problems and help the construction industry accept and adopt the AR technology.

Sub question 2 → What are the benefits of using AR in the construction industry?

Augmented reality will improve the scheduling aspect of the construction industry greatly; it can show an as-planned vs. an as-built structure to allow visualization of progress (Zollmann, et al., 2014). Access to project information on-site is significantly improving with the introduction of different augmented reality (AR) programs compared to more traditional information sources (Pejoska , Bauters, Purma , & Leinonen, 2016). These AR systems allow fast access to information helps project managers to decide on corrective actions to minimize cost and delays due to performance discrepancies (Bae , Golparvar-Fard, & White , 2013). These new AR programs give multiple parties associated with a construction projects the ability to clearly grasp the whole picture of the project site and to make accurate predictions about future activities (Lin, Liu , Tsai , & Kang , 2014). The added visualization benefits of AR technologies allow for better communication between parties when commenting and making suggestions for a particular project (Hsieh, Kang, & Lin, 2016).

In specific, if managers know the core control time points and measures for works to be checked proactively through the defect domain ontology, then the worker's performance can be automatically checked at the right time with BIM and AR applied inspection tools without visiting the workplace (Park, Lee, Kwon, & Wang , 2013). Allowing managers to save both time and money on specific projects while lowering Man-Labor hours and cost efficiencies due to defects and construction rework. Much money and time are wasted because plans or drawings are misinterpreted, or the information is transferred imprecisely from the plan to the real object (Wang , Truijens, Hou, Wang, & Zhou , 2014).

Also, by using augmented reality, the total cost of “the same knowledge that needs to be imparted with respect to safety, could be reduced dramatically” (Agrawal , Acharya , Balasubramanian, Agrawa, & Chaturvedi, 2016). The total cost of using augmented reality is cheaper because the equipment used could vary from high end gear to a simple smartphone. A smartphone could be use because of the infinite possibilities that applications provide. “Augmented reality applications are cheaper and more efficient ways to enhance human safety” (Agrawal , Acharya , Balasubramanian, Agrawa, & Chaturvedi, 2016).

Sub question 3 → What are the construction stages of interest concerning the implementation of AR?

The literature shows that AR is presumably beneficial throughout the whole project phase. The life cycle of a construction project consists of a sequence of steps or project phases (figure 7) to be completed in order to reach project goals and objectives. These phases are defined by N. Dawood (2009) as: (2) initiation and outline design, (3) design development, (4) [procurement], contract and pre-construction, (5) construction, and (6) maintenance (Rankohi & Lloyd, 2013).

In addition to the project phases, Augmented reality technology has many applications in the construction industry. In this research the classification of Rankohi and Lloyd (2013) is used to classify AR application areas in the industry (figure 7) as follows: (1) visualization or simulation, (2) communication or collaboration, (3) information modeling, (4) information access or evaluation, (5) progress monitoring, (6) education or training, and (7) safety or inspection.

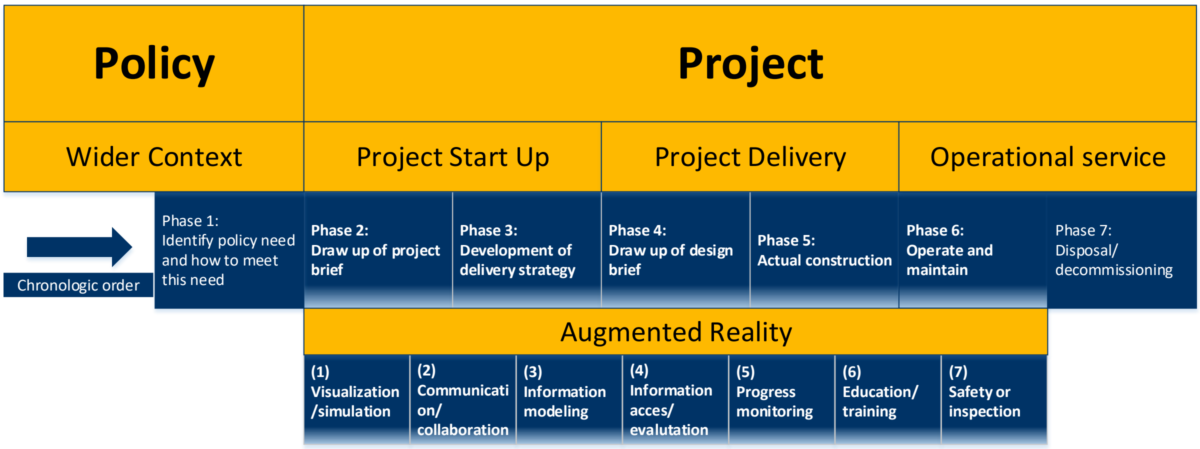

Figure 7, Project delivery phases and classification AR (Dawood, 2009; Rankohi & Lloyd, 2013)

Method

This chapter explains the research methods that were used in this report.

3. Methodical justification

As stated in the literature research, the construction industry struggles with the adoption of AR. Some of the main (container) obstructions to the adoption are, “immature core virtual reality technology, conservative nature of construction businesses, size of building information models” (Meža, Turk, & Dolenc, 2015), relative high costs of AR technology, hardware issues and the scarcity of AR application specifically designed for the construction industry (Silverio, Renukappa, & Sures, 2017).

AR is still relatively in its early stages of development pertaining to the construction industry, but it is already showing great potential (Behzadi, 2016). The implementation of this technology looks like the definite future for the construction industry, despite that some present limitations slow down its implementation, the possible applications are promising, such as visualization of technical information on the job site, visualization of spatial model for design and marketing (Silverio, Renukappa, & Sures, 2017).

Alsafouri, Ayer, & Tang emphasize the importance of investigating a method to help the construction industry accept and adopt AR technology by realizing the benefits it includes (Alsafouri, Ayer, & Tang, 2015; Calderon-Hernandez & Brioso, 2018). According to the literature, ‘implementation’ is the main area of concern for proposed future work. Therefore, it’s necessary to establish the obstructions concerning the implementation of AR in order to be able to help the construction industry accept and implement AR technology.

3.1. Method

In order to identify the obstructions concerning the implementation of AR, Theoretical, and Qualitative research was conducted. First, theoretical research was conducted by literature research on the following topics concerning the (Dutch) construction industry: Augmented Reality, automated monitoring, and Big Data concerning AR-systems. Then qualitative research was conducted in the form of interviews with experts on the topic (AR) from different parties in the construction industry. Data derived from the theoretical and qualitative research was structured and categorized using the Grounded Theory resulting in a list with the obstructions per source (Gallicano, 2013).

Because the obstructions were derived from two sources (literature research and qualitative research), Methodological Triangulation was used to see if similar results were found. If the conclusions from the two methods were the same, validity was established (Guion, Diehl, & McDonald, 2014).

The list with considered obstructions was converted into a survey wherein the attributing values of the obstructions varied from 1 until 9. The scale determined the relative importance of an alternative when compared with another alternative. This survey was presented to experts on the topic, who graded the obstructions according to their perceived level of importance. Structuring the survey in such way, made it possible to use the Fuzzy TOPSIS method for analyzing the data and calculating the ranking of the obstructions (Velmurugan & Subramanian, 2011). Hence, the Fuzzy TOPSIS method was used to determine the most important obstructions concerning the implementation of AR.

After ranking the obstructions, enablers of the highest ranked/most important obstructions were described. Providing insight into who or what caused the obstructions and how to overcome them. Considering that, the first few steps towards successful implementation of AR in the construction industry were described.

A visual representation of the methodological justification is displayed in the research model (chapter 3.2., figure 8).

3.2. Research model

Below (figure 8) the philosophical underpinning of the research methods is visualized in the form of a research model.

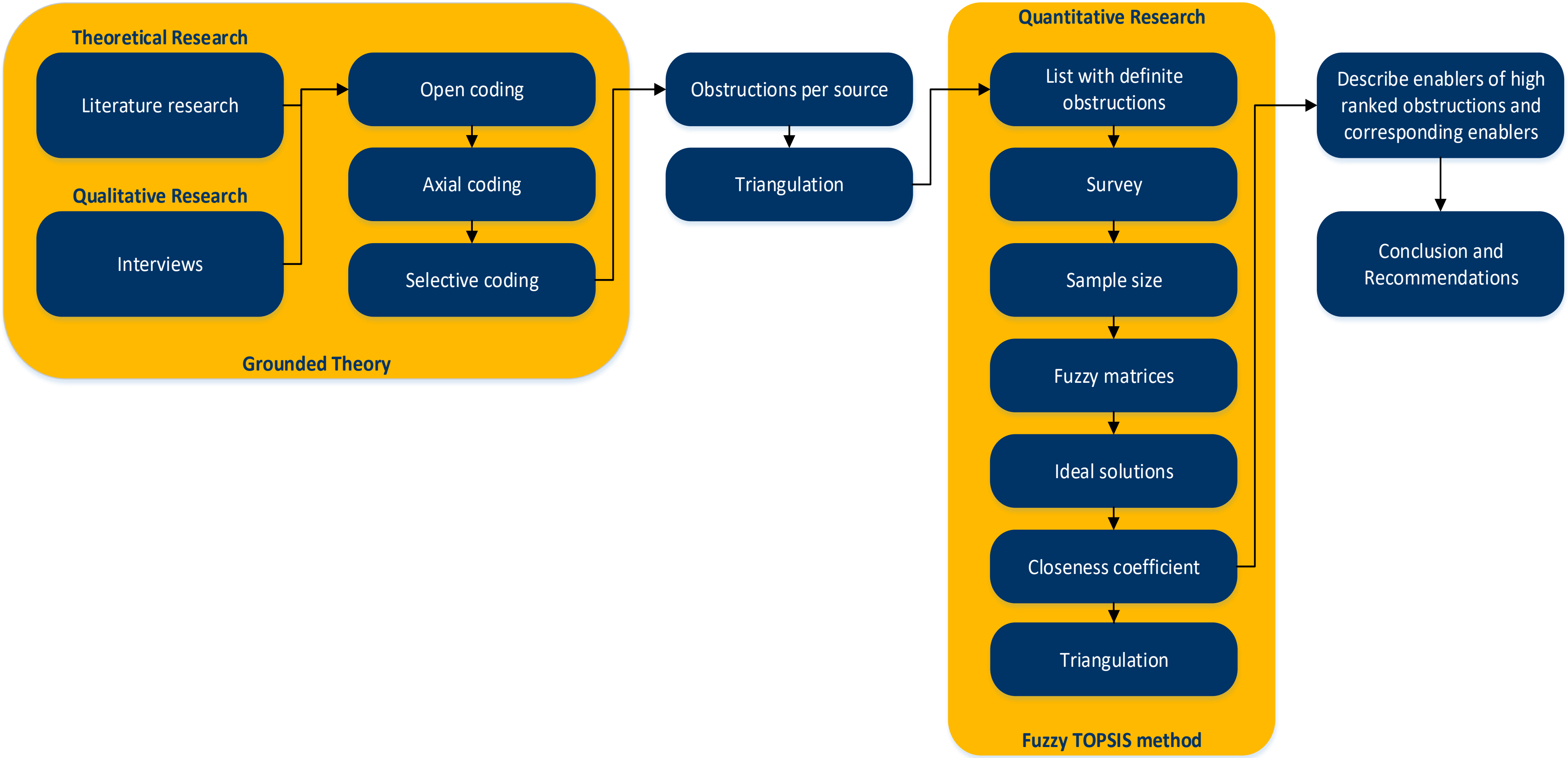

Figure 8, Research model

3.3. The Grounded Theory

Grounded theory involves the progressive identification and integration of categories of meaning from data. It is both the process of category identification and integration (as method) and its product (as theory). The Grounded theory as method was used to provide the guidelines to identify categories, on how to make links between categories and how to establish relationships between them. Grounded theory as theory, was the end-product of this process; it provided an explanatory framework with which the phenomenon under investigation could be understood (MH education).

3.3.1. Coding

Basically, the Grounded Theory generates the building blocks of the analysis. Theoretical analysis will assemble these building blocks into a functioning building. Hence, coding shapes the analytic frame from which the analysis is built. Coding is the pivotal link between collecting data and developing an emergent theory to explain these data. Through coding can be defined what is happening in the data, and it's possible to grapple what it means (Charmaz K. , 2006).

Open coding

Coding gets the research off the empirical level by fracturing the data, and then conceptually grouping it into codes that then become the theory which explains what is happening in the data (Glaser E. G., 1978). First, open coding was used to pull together and categorize a series of otherwise discrete events, statements, and observations which could then be identified in the data (Charmaz K. , 1983; Lawrence & Tar, 2013)

Axial coding

Then, Axial coding was used for re-building the data (fractured through open coding) in new ways by establishing relationships between categories and their subcategories. It is termed "axial" because coding occurs around the axis of a category, linking categories at the level of properties and dimensions (Strauss & Corbin, 1998). The axial codes represent categories that describe the open codes. Thereafter coding was continued, comparing the concept to more incidents (Glaser E. G., 1978). Comparison enables the identification of variations in the patterns to be found in the data. Data coding at this level is intended to elevate the data to higher levels of abstraction (Hutchinson, 1988) (Lawrence & Tar, 2013).

Selective coding/categorization.

The last step used selective coding to integrate and refine the categories into a theory, which accounts for the phenomenon being investigated (Darke, Shanks, & Broadbent, 1998) and validates the statements of relationships among concepts, and fills in any categories in need of further refinement. Selective coding reduced the data from many cases into concepts and sets of relational statements that were used to explain, in a general sense, what is going on (Strauss & Corbin, 1998; Lawrence & Tar, 2013) Categories in grounded theory emerge from the data, they are not mutually exclusive, and they evolve throughout the research process (MH education).

3.3.2. Data collection

For gathering initial data, literature research was conducted. To make this research as complete as possible, additional document research was performed in order to find as many obstructions as possible. The findings of the document research were processed using the grounded theory.

When using the grounded theory, theoretical sampling is recommended. Theoretical sampling involves the procedure of choosing participants who have experienced or are experiencing the phenomenon, in this research that was AR in the construction industry. By doing so, 'experts' in the phenomenon are chosen and thus able to provide the best data (Corbin & Strauss, 1998; Glaser &

Strauss, 1967). The process of selecting experts was an evolving process based on the arising patterns, categories, and dimensions emerging from the data (Thomson, 2016). A phenomenological study may involve single, one-hour interviews with 5-20 participants (Van Note Chism, Douglas, & Hilson, 2008). Because the interviews were supplemented by document research, it was proposed to start with five experts. Since there were not many parties (within the Dutch construction industry) that specialize in AR, this research aimed to interview the leading parties within the construction industry. By consulting experts within the industry, the leading authorities were established.

3.4. Triangulation of the data

Triangulation is a method used in qualitative research to check and establish the validity of a study by analyzing a research question from multiple perspectives. Patton (2002) cautions that it is a common misconception that the goal of triangulation is to arrive at consistency across data sources or approaches; in fact, such inconsistencies may be likely given the relative strengths of different approaches. In Patton's view, these inconsistencies should not be seen as weakening the evidence, but should be viewed as an opportunity to uncover deeper meaning in the data (Guion, Diehl, & McDonald).

3.4.1. Methodological triangulation

Methodological triangulation involves the use of multiple qualitative and/or quantitative methods to study the program. For example, results from surveys, focus groups, and interviews can be compared to see if similar results are being found. If the conclusions from each of the methods are the same, then validity is established (Guion, Diehl, & McDonald). Because this research involves multiple qualitative methods, literature research, and interviews with different stakeholders/parties, methodological triangulation was used. This way, participants that were able to provide a deeper understanding concerning these aspects could be pointed out.

3.5. Fuzzy-TOPSIS Method

The Fuzzy-TOPSIS methodology is a method for multi criteria decision making (MCDM).

The TOPSIS method was developed by Hwang and Yoon (1981) to provide a solution for MCDM problems. Kim et al. (1997) stated the advantages of a TOPSIS as follows:

- A sound logic that represents the rationale of human choice;
- a scalar value that accounts for both the best and worst alternatives simultaneously; and
- a simple computation process that can be easily programmed into a spreadsheet.

TOPSIS is useful, particularly when there are a large number of alternatives and criteria. In such cases, methods like AHP, which requires pair wise comparison, are avoided. Also, TOPSIS has the fewest rank changes reversals when an alternative is added or removed in comparison to other MCDM methods (Zanakis et al. 1998). These advantages make TOPSIS a major MCDM technique as compared with other related techniques, such as analytical hierarchical process (AHP) and ELECTRE. The traditional TOPSIS method considers ratings and weights of criteria's in crisp numbers. However, crisp data are inadequate to represent the real-life situation since human judgments are vague and cannot be estimated with exact numeric values. In such situations, the fuzzy set theory is useful to capture the uncertainty of human judgments. What made it the best possible fit for this research. Zadeh (1965) first introduced fuzzy set theory into MCDM including TOPSIS as an approach for effectively working with the vagueness and ambiguity of the human judgments. In fuzzy TOPSIS, all the ratings and weights are defined by means of linguistic variables. Below, the two main characteristics of fuzzy systems by Kahraman et al. (2007) are given:

- Fuzzy systems are suitable for uncertain or approximate reasoning, especially for the system with a mathematical model that is difficult to derive; and
- Fuzzy logic allows decision-making with estimated values under incomplete or uncertain information. Because of all these advantages, fuzzy logic has been combined and used along with TOPSIS known as fuzzy- TOPSIS methodology.

(Agrawa, Singh, & Murtaza, 2016)

Analysis

This chapter explores the data, derived from the methods discussed in the last chapter, in order to explore the meaningful insights.

4. Analysis

As discussed in chapter 3, interviews with experts concerning AR in the construction industry is the main component of the information gathering process. Supplemented with the other data gathering techniques: document research and attending activities/meetings concerning the subject. The raw data was processed using coding, of which the selective coding contains the obstructions or enablers. These obstructions and enablers were then categorized using the particular codes and after that triangulated. With the definite obstructions determined, a survey was designed applicable to the Fuzzy-TOPSIS method. Using this method, a ranking of obstructions was established. By keeping the data sources separated, to identify similarities and differences between the different fields of expertise, applying triangulation was possible.

4.1. Interviews

Before the interviews started, document research was performed and finished. Based on this, the interview questions were composed, and the interview, in appendix 1, was compiled.

The experts for the interviews were selected based on the indication of other experts. Firstly, based on conversations with employees within Heijmans, an expert concerning AR within Heijmans was interviewed (Ginneken, 2019). During the interview, the expert was asked which persons and companies, according to him, are authorities in the field of AR. This was done during every interview, to map the leading authorities within the Dutch construction industry as well as possible. Initially, the proposed number of interviews was five. But on the direction of the interviewed experts, two additional interviews were conducted. Eventually, the seven experts displayed in table 3 were interviewed. All interview transcripts can be found in supplement 1.

Table 3, Information interviewed experts (source: supplement 1)

Interviewed experts			
Name:	**Function:**	**Company:**	**Date:**
Giel van Ginneken	Project coordinator	Heijmans	03-07-2019
Sander Baas	Project Manager	Royal HaskoningDHV	16-07-2019
Lars ter Steege	Advisor	Studio-X	17-07-2019
Thomas Smits	BIM-Advisor	Heijmans	25-07-2019
Job van Hardeveld	Consultant AEC	Cadac Group AEC BV	02-08-2019
Danny Oldenhave	Operational Director	Atos	07-08-2019
Gino van der Zijde	Business Developer	Unit 040	20-08-2019

4.2. Converting the raw data to axial codes

For converting the raw data, a coding table was used. The useful information gathered from the interviews and the document research was copied into the first column of the table. Then this data was fractured in the second table using open coding. In the last column of the table, the fractured data was re-build, using axial coding, establishing relationships between categories and their subcategories.

Table 4, Example of coding table: Obstructions – Interviews (source: supplement 2)

Coding table, Obstructions – Interviews		
Obstructions - Interviews		
Raw data	**Open coding**	**Axial coding**
Op het moment dat wij als afdeling met bijvoorbeeld nieuwe VR/AR en of mixed reality's technologieën komen, willen zij eigenlijk dat deze technologie zich al heeft bewezen. Dat ze weten, dat als ze deze technologie toepassen in een bepaalde situatie, kunnen we zo ongeveer 30% te besparen. Het kost veel moeite om dit te doorbreken, bij het ene project lukt dit beter dan bij het andere. Met AR is dit nog niet gelukt, toegevoegde waarde moet eerst bewezen worden (denk hierbij aan kosten reductie onderaan de streep). (Smits, 2019)	Added value not yet proven Traditional culture	Conservative nature Hardware limitations Invisibility of added value
Als het echt op AR aankomt, denk ik toch als snel aan een iPad enz., dat je met de camera filmt en (BIM model) objecten toevoegt met een app aan de werkelijke omgeving. Hierbij merk ik dat het maar tot op zekere hoogte werkbaar is. (Smits, 2019)	Limited operational use	

The information per data source was kept separate, so that the data could be traced back to the source in a later stage. Also, two separate coding tables were established for both the obstructions and the enablers, making discerning easier. Hence, in total four tables were established. An example of the coding tables is displayed above in table 4, herein can be seen how the raw data was converted to axial codes. For an overview of the coding tables see supplement 2.

4.3. Categorization

From the raw data, 59 axial obstruction codes and 93 axial enabler codes were derived. Selective coding was then used to integrate and refine the axial codes into a theory. Reducing axial codes into categories, that was used to explain what's going on in general sense.

As a pad for selective coding, emerged during the literature research in chapter 2, the classification of Rankohi and Waugh (2013) was used. They classify AR application areas in the construction industry (figure 7) as follows: (1) visualization or simulation, (2) communication or collaboration, (3) information modeling, (4) information access or evaluation, (5) progress monitoring, (6) education or training, and (7) safety or inspection.

Because the model classifies AR applications and not obstructions/enablers concerning the implementation in the Dutch construction industry, the model was modified. Visualization or simulation, in combination with progress monitoring, was translated to selective code: technological. Information modeling and information access or evaluation were merged into informational. Furthermore, organizational was added to include the aspect that involves a part of or the organization as a whole. The economic aspect that isn't present was added as selective code financial. As of last, the cultural stance concerning new technology was included as awareness, which resulted in the nine selective codes: organizational, communicational/collaboration, informational, financial/economical, technological, awareness, operational, educational/training, and safety. Each selective code is defined below, within the context of this research.

Organizational

The category organizational concerns the organizational structure, a system that outlines how certain activities are directed in order to achieve the goals of an organization (Kenton, 2019). Hence, the organizational structure determines how and if AR is directed within the organizations.

Communicational/collaboration

Communication within an organizational context is defined as the sending and receiving of messages among interrelated individuals within a particular environment of setting to achieve individual and common goals (Organizational Communication, sd). Successful implantation of AR rests on proper collaboration and communication.

Informational

Organizational information derives its meaning from the sense-making frameworks that characterize specific organizations. In order to set op AR technology within an organization, members/systems need information in order to fulfill their responsibilities. So, other members/sensors gather the data and convert it into information (Starbuck & Porrini, 2001). If the necessary information is incorrect or missing, AR systems can't function.

Financial/economical

Financial, in this particular context, is defined as the part of an organization that manages the money (Business Dictonary, 2019), including forecasting and planning, monitoring cash flows, accounting, decision making, and measuring results. The development, implementation, and use of AR are linked to financial costs and the possible benefits.

Technological

Technological within this context is defined as the application of AR technology for practical purposes in the construction industry. This including the technological obstructions that hold back development, implementation, and use. On the other site, possibly resulting in improvements in technical processes that increase the productivity of machines and eliminate or make manual operations more efficient or operations done by older machines.

Awareness

In this context, awareness is mostly regarded as AR technology awareness. This involves being mindful and being able to recognize and understand new the new technology and that it could be useful for the success of the business (CLEVERISM, 2019).

Operational

By operational is meant everything that happens within a construction company to keep it running and earning money referred to collectively as business operations. Examples of this are construction, alteration, repair, extension, demolition or dismantling of buildings or structures. Selective code operational refers to all business operations concerning the AR technology in the industry.

Educational/training

Training implies the act of imparting a special skill or behavior to a person concerning AR technology, which is commonly offered to employees of the operational level. Additional to training, the element of education is involved, which refers to the process of systematic learning something concerning AR technology in an institution that develops a sense of judgment and reasoning in employees.

Safety

Safety in construction aims to ensure that a construction site or the industry as a whole is not the cause of immediate danger to the public around a construction site, or the workers at a construction site, as well as making sure that the finished product of construction meets required safety standards. (Safeopedia Inc., 2019)

Table 5, Part of categorization table; Obstructions – Interviews (source: supplement 3)

Categorization table, Obstructions - Interviews			
Selective coding			
	Organizational	**Communicational/ collaboration**	**Informational**
Obstructions Interviews	(1) Conservative nature (2) Short term result-oriented (3) Not company-wide adopted/implemented (4) Limited will to invest (5) Mostly depending on experts (6) Too many decision-makers	(7) Poor intern and extern collaboration (8) Afraid of controlling function (9) No clear definition of AR (10) Misleading advertisement/impressions	(11) Quality BIM-model (12) Poor information management (13) Fragmentation of knowledge (14) Delayed information flow

Table 5 displays a section of the categorization table. In which, every column was categorized, making use of selective coding, amounting to a total of nine columns. Again the information per data source was kept separate. So that the data could be traced back to the source in a later stage, the complete categorization table can be found in supplement 3.

4.4. Triangulation per category

A simplified overview of the categorized obstructions and enablers, using the code numbers, is displayed below (table 6). Triangulation was used in order to find the similarities between the obstructions and between the enablers within a category. So, within each column, the obstructions derived from the interviews and the obstruction derived from the document research were compared to each other. Similar codes were recoded into one, or an all-embracing code was used to describe the two or more overlapping codes. Before describing the triangulation process, similar codes within a category were highlighted, using a different color for each similarity. Codes that were excluded during the process were crossed out. An overview of the triangulation table can be found in supplement 4.

Table 6, categorization of the obstructions and enablers by number (source: supplement 3)

Categorization									
	Selective codes								
	OR	CO	IN	FI	TE	AW	OP	ED	SA
Obstructions Interviews	1, 2, 3, 4, 5, 6, 7, 8, 9	10, 11, 12, 13	14, 15, 16, 17	18, 19, 20, 21, 22, 23	24, 25	26, 27, 28, 29, 30	31, 32, 33, 34		35
Obstructions Document-Research	36, 37, 38, 39		40, 41, 42, 43	44, 45, 46, 47	48, 49, 50, 51, 52, 53, 54	55, 56, 57	58		59
Enablers Interviews	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16	17, 18, 19, 20, 21, 22, 23	24, 25, 26, 27, 28	29, 30, 31, 32	33, 34, 35, 36, 37, 38, 39, 40	41, 42, 43, 44, 45, 46	47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62	63, 64	65, 66
Enablers Document-Research	67	68, 69, 70, 71	72, 73	74	75		76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90	91	92, 93

4.4.1. Obstructions

Concerning the obstructions, quite some similarities were found. The first similarity in the category organizational is the conservative nature of the construction industry, codes 1 and 40, that are almost exactly the same. Therefore, code 40 was excluded. Within the obstructions from the interviews, codes 2, 4, and 9 are interrelated. Both limited will to invest (code 4) and short investment horizon (code 9) are effects of wanting to achieve short-term results and were therefore excluded. Also, codes 3 and 5 are interrelated within the obstructions from the interviews. Because AR is often not companywide adopted, the technology usually depends on one or a few experts within the company. That's why code 5 was not included in the final obstructions.

Concerning the category communicational/collaboration, no substantial similarities between the codes were found.

Category financial includes the code (poor) data management (code 42), which is a part of (poor) information management (code 15). Poor information management is one of the causes of delayed information flows. Code 14, quality of the BIM-models, is co-determined by the structure of the BIM-model (code 40) and was therefore included.

Then in the category financial/economical, the codes tight project budgets (19) and increased cost within budgets (45), result from the cost recovery structure/project cost accounting (code 23) that is used. Because, when for example, AR is funded centrally and separate from the project, it doesn't affect other budgets. Hence, code 19 and code 45 were excluded. Large initial investment (code 22) is similar to high initial investment (code 46), and so code 46 was excluded. High development and implementation costs are an example of the large initial investment that's associated with AR. Within the obstructions derived from the literature research, difficulties with quantifying the RoI (code 47) can be seen as one of the reasons why there is uncertainty about the RoI (code 44) concerning AR. Hence, code 47 was excluded, but to be including, code 44 was supplemented as follows: uncertainty about RoI (for example, difficulties with quantifying RoI).

In category technological, both obstructions derived from interviews and document research, contain the code hardware limitations (codes 24 and 48). Naturally, these were coded into one. Converting issues (BIM to AR) (code 50) and communication issues (software related) between BIM model and AR device (code 52) are part of the complex software processes (code 25). Therefore, code 25 was recoded into complex software processes, including software and communication issues converting BIM to AR.

Thereafter, category awareness was reviewed. Code 28, no/limited similar (beneficial) use cases, and code 56; no/lack of successful use cases, are almost the same. Code 28 gives the most including description, and so code 56 was excluded. Limited awareness within the industry (code 29) is too general defined and amounts to the same as unfamiliarity with AR (code 57). Hence, limited awareness within the industry (code 57) was excluded.

At first, no similarities were found in the category operational. But after looking at the next two categories, educational/training and safety, it was decided there were not enough axial codes to maintain these categories. Since all the axials codes under these categories refer to education/training and safety on an operational level, the categories education/training and safety are merged into the already existing category operational.

After the merge, two codes that show overlap was found, code 35 and 59. Both refer to the safety issues of AR concerning the operational aspect of construction. But code 35 refers to the psychical safety issues on the construction site and code 59 to ruggedness of the hardware (for example, the reliability of AR devices). Hence, these codes were defined to abstract and needed to be specified in order to prevent confusion. Code 35 was recoded into physical safety issues using an AR device. Code 59 was recoded into ruggedness issues making hardware compliant with safety standards (for example, privacy when processing data). Table 7 displays the condensed list with definite obstructions after triangulation.

Table 7, Condensed list with definite obstructions (source: supplement 4)

Condensed list definite obstructions		
Category	**Code**	**Obstructions**
C1: Organizational	**OR1**	Conservative nature of the construction industry
	OR2	Short term result oriented
	OR3	Not company-wide adopted/implemented
	OR4	Too many decision makers
	OR5	No sustainable strategy concerning AR
	OR6	Insufficient capacity because of the growing construction market
	OR7	Hard to come by experts/technicians
	OR8	Using 3D and 4D models, not construction industry-wide adopted
	OR9	Problems integrating/matching AR in current processes
C2: Communicational /Collaboration	**CO1**	Poor intern and extern collaboration
	CO2	Afraid of the controlling function ("big brother is watching you")
	CO3	No clear definition of AR
	CO4	Misleading advertisement/impressions causing unrealistic expectations
C3: Informational	**IN1**	Poor quality of (BIM) models
	IN2	Poor information management
	IN3	Fragmentation of knowledge
	IN4	Lack of standardization in information concerning technology tools
	IN5	Lack of commitment to support the information source/model
C4: Financial /Economical	**EC1**	Invisibility of added value
	EC2	Added value currently not high enough for customer/client
	EC3	Large initial investment
	EC4	Wrong cost recovering structure/project cost accounting, no central funding for new technology
	EC5	Uncertainty about Return on Investment (RoI), for example, difficulties quantifying the RoI
C5: Technological	**TE1**	Hardware limitations
	TE2	Complex software processes, including software and communication issues converting BIM to AR
	TE3	Lack of user-friendly applications
	TE4	Quality of the visuals, for example, occlusion issues and resolution of the visuals
	TE5	Lack of dedicated software
	TE6	The AR field is vast and diverse
C6: Awareness	**AW1**	Insufficient knowledge on AR (what is AR)
	AW2	Fear for Job replacement
	AW3	No/limited similar (beneficial) use cases
	AW4	Pigeonholing, only looking at it from one's own perspective
	AW5	Lack of acceptance by professionals in the construction industry
	AW6	Unfamiliarity with AR (what are the possibilities with AR)
C7: Operational	**OP1**	Time-consuming (to make it operational)
	OP2	Additional risk within projects for including AR
	OP3	Not workable in construction environments
	OP4	Change in current processes
	OP5	Physical issues using an AR device (Motion sickness (for example the HoloLens))

	OP6	Ruggedness issues, making hardware compliant with safety standards

4.4.2. Enablers

Concerning the enablers, also quite some similarities between the axial codes were found. The first category, organizational, includes creating a budget for innovation (code 1). Which is already included in organization based funding (instead of project-based funding). Because, by organization based funding is meant, creating a central funding/budget for enabling the use of AR in the organization. Product thinking, instead of project thinking (code 3), is part of standardizing processes (code 40). Because in order to create standardization, standard products within different projects need to be defined. Bad economy allows for innovation (code 11), is an enabler of AR, but not one that can be initiated by a person or organization and is therefore excluded.

Well defined business cases, code 9, is related to defining concrete applications for AR, code 13. In order to define a business case concerning AR, there has to be a concrete application for AR within the business case. Hence, code 9 and 13 were merged into code 14: well-defined business case, containing a concrete application for AR.

In the category communicational/collaboration, both the enablers derived from the interviews and the enablers derived from the document research, the same code, improve stakeholder management (18 and 64) can be found. Therefore one of the codes, code 64, was excluded. The same goes for code 19 and 63, improve communication. Hence also, code 63 was excluded. Code 23 and 66 look similar because they both concern the decision-making process. But code 23, involves the decision-makers, meaning including the people that are authorized to make decisions about AR within an organization — for example, making an investment of a certain amount for developing AR software. Code 66, improve stakeholder management, aims at improving the decision making process itself (making it faster, easier, etc.).

Category informational contains no similarities. (BIM) Model information structuring (code 24) seems to be a part of efficient information management (code 67). However, code 67 refers to delivering the right information as efficient as possible, to the right place at the right time. Code 24, on the other hand, concerns the “construction” information within the (BIM) model.

One similarity was found in the category of financial/economical. Code 29, often already profitable, is an effect of code 69: higher cost efficiencies. Because when the cost efficiencies become larger, the chance of profitability increases. Therefore, code 29 was deleted.

Then, in the category technological, two almost identical codes were found. Code 70, includes defect and error detections, while code 33 only includes error detection. Being the most inclusive code, code 70 was retained, and code 33 excluded. Next, two similarities from the same data source were found. Improving the hardware for automating process monitoring (code 35) means the hardware must also be capable of measuring automatically (code 34). To show this coherence, code 34 and 35 were merged into code 36: improving the hardware for automated process monitoring and automated measuring.

Again, in the category awareness, two similarities derived from the same data source were found. Creating awareness (code 43) is too general defined and amounted to the same as familiarity with AR (code 44). Hence, creating awareness (code 43) was excluded.

Supporting optimization of processes (code 49) is the discipline of adjusting a process to optimize a certain specified set of parameters without violating any limitation. The most common goals are to minimize costs and maximize throughput and/or efficiency. Therefore the codes: working more efficiently (48), reducing the lead time (51), reducing construction project time (83), and lowering labor work/time (86) are already covered by code 49 and so excluded. Also code 77, supporting optimization of processes, has exactly the same meaning as code 49 and was excluded. Remote guidance and supervision (code 82) already covers on-site direction (code 50), and so this code was also excluded. Improving construction quality (code 53) was excluded because it's a result of better quality management (code 76). Within the enablers derived from document research, design reviews (code 55) and verification of simulation (code 57) amount to the same. Code 57 gives the most complete description, and so code 55 was excluded. The same goes for verification of simulation (code 58), which includes simulation of scenario's in the real world (code 56). Therefore code 56 was excluded.

As already described, in chapter 4.5.1. Obstructions, there were not enough axial codes for maintaining the categories of educational/training and safety. Again, all the axials codes under these categories refer to education/training and safety on an operational level; therefore, categories education/training and safety are merged into the already existing category operational. Then some more similarities were found. More efficient training of personnel (code 60) and more effective training/education, complement each other, and were merged into one code (90). Code 90 was formulated as more effective and efficient training/education. Improving safety in construction environments (code 61) and safer way of working (code 62), are included in the code improve safety (88). Therefore, code 61 and code 62 were excluded. Below, in table 8, a condensed list of the enablers, after triangulation, is displayed.

Table 8, Condensed list with definite enablers (source: supplement 4)

Condensed list definite enablers		
Category	**Code**	**Enablers**
C1: Organizational	**OR-E1**	Organization based funding, instead of project based funding
	OR-E2	Standardizing processes
	OR-E3	Incorporating AR into the vision and strategy of the company
	OR-E4	Seeing AR as means to achieve a goal
	OR-E5	Using market/innovation pull
	OR-E6	Adapt service structure, that avoid high initial investments
	OR-E7	Improved process control
	OR-E8	Bad economy allowing for innovation
	OR-E9	Become agile, allowing for fast and easy adaption to change
	OR-E10	Well defined business case, containing a concrete application for AR
	OR-E11	Coordinated way of thing concerning AR
	OR-E12	Distinguishing value for the tender mechanism
	OR-E13	Reducing mistakes and effects

C2: Communicational /Collaboration	**CO-E1**	Knowledge sharing
	CO-E2	Improving stakeholder management
	CO-E3	Improving communication
	CO-E4	Clear definition of AR and what it includes
	CO-E5	Creating trust
	CO-E6	Involve authorized key-decision makers
	CO-E7	Making interaction tangible
	CO-E8	Improve decision-making process
C3: Informational	**IN-E1**	Proper structuring of information in (BIM) models
	IN-E2	Providing insight in the design
	IN-E3	Making information centrally visible
	IN-E4	Traceability of work or service
	IN-E5	Run information flow parallel to the process
	IN-E6	Efficient information management
	IN-E7	Improves 4D scheduling
	IN-E8	Introducing universal protocol
C4: Financial /economical	**EC-E1**	Fewer failure costs
	EC-E2	Advancing feasibility study
	EC-E3	Reducing consultancy costs
	EC-E4	Higher costs-efficiencies
C5: Technological	**TE-E1**	Improving the hardware for automated process monitoring and automated measuring
	TE-E2	Device-independent
	TE-E3	Universal software for converting BIM to AR
	TE-E4	Modular construction of the technology for reusability in different situations
	TE-E5	Compensation of hardware limitation with software
	TE-E6	Defect/error detection
C6: Awareness	**AW-E1**	Including AR in tenders
	AW-E2	Making the added value of the technology visible
	AW-E3	Make the construction industry familiar with the new technology
	AW-E4	Rejuvenation in the construction industry
	AW-E5	An example of an (successful) use-case
C7: Operational	**OP-E1**	Improving executability of difficult work
	OP-E2	Supporting optimization of processes
	OP-E3	First-time-right implementation
	OP-E4	Development in small manageable steps
	OP-E5	Digital/testing simulations
	OP-E6	Verification of digital/testing simulations
	OP-E7	Providing work instructions
	OP-E8	Improving quality management
	OP-E9	Enhance scheduling
	OP-E10	Enhance visualization
	OP-E11	Enhance progress tracking
	OP-E12	Faster maintenance interventions
	OP-E13	Remote guidance and supervision
	OP-E14	Supplement shortcoming of on-site BIM use on constructions sites
	OP-E15	Enabling site navigation
	OP-E16	Improve safety

	OP-E17	Cheaper and more efficient way to enhance human safety
	OP-E18	More efficient and effective training/education

An overview of all the definite obstructions and enablers, per source, can be found in appendix 2.

4.5. The Survey

After triangulation of the data a list of obstructions per selective code/category was established in table 7. These are the definite obstructions used in the survey for ranking the obstructions. The survey was made in SurveyMonkey (online survey software that helps to create and run professional online surveys (Ramshaw, n.d.), and sent out by email to experts on AR using a web link.

4.5.1. Collecting the required data

The data was collected using the linguistics terms: Not Important (NI), Less Important (LI), Neutral (FI), Important (I) and Very Important (VI). These linguistics terms must be converted into fuzzy numbers. In a fuzzy set theory, a triangular fuzzy number (TFN) $\tilde{\alpha}$ can be defined by triplet (a_1, a_2, a_3), as displayed in figure 9 (Agrawa, Singh, & Murtaza, 2016).

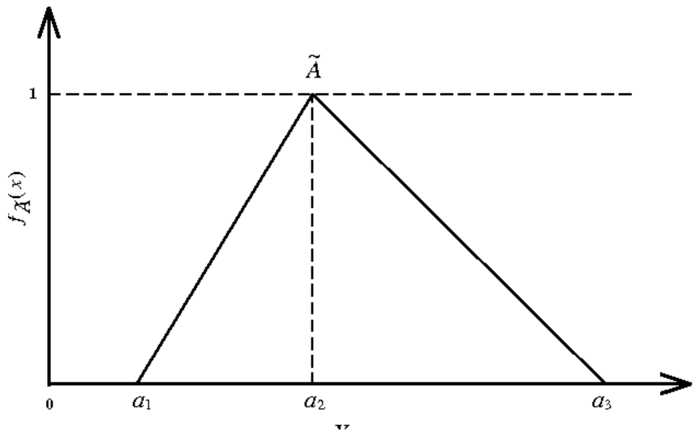

Figure 9, Triangular fuzzy number (Deshmukh & Borade, 2019; Agrawa, Singh, & Murtaza, 2016)

Wherein, parameter a_1 indicates the smallest possible value, parameter a_2 indicates the most promising value, and parameter a_3 indicates the largest possible value that describes a fuzzy event (Gligoric, Beljic, & Simeunovic, 2010). Conversion scales were applied to transform the linguistic terms into fuzzy numbers. The membership function $f_{\tilde{A}}(X)$ (function 1 (Kaufmann & Gupta , 1985)) is defined as:

$$f_{\tilde{A}}(X) = \begin{cases} \dfrac{x-a_1}{a_2-a_1}, & a_1 \le x \le a_2 \\ \dfrac{a_3-x}{a_3-a_2}, & a_2 \le x \le a_3 \\ 0, & otherwise \end{cases} \quad (1)$$

A 1-9 scale was used (figure 10) for rating the obstructions, table 9 below provides the linguistic terms and corresponding triangular fuzzy numbers. The TFN's were set up with equal distances between the different variables. Such that the linguistic term: fairly important, is exactly in the "middle' with no preference for a side. (Deshmukh & Borade, 2019)

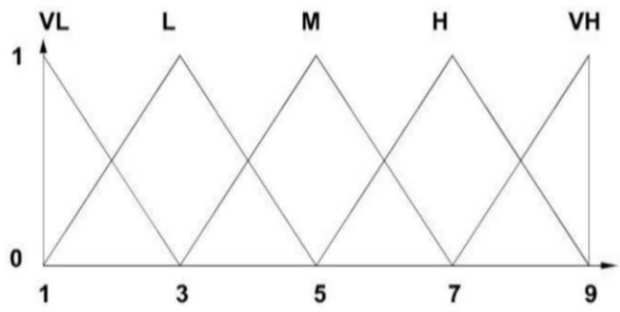

Figure 10, Linguistic scales and triangular fuzzy numbers (Deshmukh & Borade, 2019)

Table 9, Linguistic terms and corresponding triangular fuzzy numbers (Deshmukh & Borade, 2019)

Scale for rating obstructions	
Linguistic term:	**Triangular Fuzzy Number:**
Not Important (NI)	(1, 1, 3)
Less Important (LI)	(1, 3, 5)
Neutral (N)	(3, 5, 7)
Important (I)	(5, 7, 9)
Very Important (VI)	(7, 9, 9)

4.5.2. Survey design

The designed questionnaire (supplement 5), enabling for data collection, consists out of 41 multiple-choice statements, divided into seven categories (1 category per page). Every statement concerns an obstruction, concerning the implementation of AR in the constructions industry, derived from interviews with experts and document research. These obstructions were rated on importance, using one of the five linguistic terms described in table 9 above.

During and through the conversations and interviews with experts (supplement 1), it was found that most experts are located in the consultancy/engineering field and some in the contractor field. Further, the construction industry is becoming more similar to other industries, for example, the production industry. In the production industry, the implementation of AR is already in a more advanced stage (Zijde, 2019). Therefore experts on AR, within other industries, could offer a different perspective rating the obstructions. Therefore, the survey was sent to experts operating in the three different fields:

- Consultancy/engineering (construction-related);
- contractors (construction-related);
- industry (not construction-related).

In order to enable data separation for these three fields of expertise, the type of company the responded works for was asked in the survey.

4.5.3. Sample size

Below the standard function for calculating sample size is displayed (function 2 (Taherdoost, 2017)). In 2017, 457,000 people (N) were employed in the Dutch construction industry. Because of the large population size, and to be able to reach a certain measure of representativeness, a confidence level of 95% (industry standard) was used with a corresponding Z-value of 1.96. A 5% error margin was sufficient because the same questions were not repeated. So, the odds they would obtain results among the 95% were nihil. Since the current conversion rate is unknown, the maximum variability of the population was set at 50% (p = 0.5) (Taherdoost, 2017).

$$\mathrm{n} = N * \frac{\frac{Z^2 * p * (1-p)}{e^2}}{\left[N - 1 + \frac{Z^2 * p * (1-p)}{e^2}\right]} \qquad (2)$$

Executing the calculation resulted in a sample size of 385.

Often organizations advertise with AR cases and applications that they can't actually deliver. They use AR almost purely for marketing and or conviction (for example, more budget), and for that purpose overpromise (Hardeveld, 2019; Steege, 2019; Zijde, 2019). Therefore, determining the exact amount of experts within and outside the construction industry is very difficult and not feasible within this study. Because this research focuses on a specialistic area within the construction industry (and industrial industry for verification), the targeted respondents were experts. Conducting web research in combination with meetings on the topic and interviews with experts, only 6 (large) contractors (Heijmans, BAM, VolkerWessels, Dura Vermeer, Van Wijnen and Ballast Nedam) could found, that are actively working on or with AR (supplement 1). Hereby is meant: real effort to make AR operational within the organization/construction industry. The number of experts per company wasn't known, assuming there had to be at least one expert per company; it was assumed at least six respondents within this field could be established.

Since it was estimated that there were not nearly 385 experts (estimated in consultation with experts (Ginneken, 2019; Zijde, 2019; Baas, Project Manager, 2019) on AR within the construction industry, it concerned experts, the survey being not the main analysis, and wanting an equal proportion of respondents per field; six respondents per field of expertise were desired. Eventually, 23 surveys were filled in and could be analyzed. Hence, the set threshold was met. Below, table 10 shows the respondents per field of expertise that filled in the survey.

Table 10, Number of respondents per field of expertise

Respondent per field		
Field of expertise		**Number of respondents**
Consultancy/Engineering Bureaus	(construction related)	10
Contractors	(construction related)	6
Industry	(not construction-related)	7
Total		**23**

4.5.4. Fuzzy decision matrix

The fuzzy TOPIS method uses the fuzzy decision matrix below (function 3). Wherin, x_{ij} (= a_{ij}, b_{ij}, c_{ij}) is a fuzzy number corresponding to by the *i*th expert (D) to the *j*th obstruction (O). i = 1, 2,…, m are the experts and j = 1,2,…, n are the number of obstructions. In this research, there were 41 definite obstructions and 23 experts that assessed these obstructions. A distinction was made between two disciplines within the construction industry, experts from engineering/consultancy bureaus and contractors. As already said, experts out of other industries (not construction-related) could offer a different perspective on the obstructions concerning the implementation and were therefore included as a distinguished third party. Separating the data sources allowed for data analysis by source, displaying the similarities and differences between them. The fuzzy decision matrix, for each field of expertise, can be found in supplement 6.

$$\widetilde{D} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1j} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2j} & \cdots & x_{2n} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ x_{i1} & x_{i2} & \cdots & x_{ij} & \cdots & x_{in} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ x_{m1} & x_{m2} & \cdots & x_{mj} & \cdots & x_{mn} \end{bmatrix} \quad (3)$$

4.5.5. Normalization of the fuzzy decision matrix

Then the raw data, from the decision matrix, was normalized using a linear scale transformation to bring the various scales onto a comparable scale. Again the data was kept separate. The normalized fuzzy decision matrices, displayed in supplement 7, was calculated as:

$$\tilde{R} = [\tilde{r}_{ij}]_{m(.)n}, \ i = 1, 2, \ldots, m \text{ and } j = 1, 2, \ldots, n \quad (4)$$

Where

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j}, \frac{b_{ij}}{c_j}, \frac{c_{ij}}{c_j}\right) \text{ and } c_j^* = \max_i\{c_{ij}\} \quad (5)$$

The weighted normalized matrix $\tilde{V}$ for criteria, was computed by multiplying the weights $\widetilde{W}_j$ of evaluation criteria with the normalized fuzzy decision matrix $\tilde{r}_{ij}$.

$$\tilde{V} = [\tilde{v}_{ij}]_{m(.)n}, \ i = 1, 2, \ldots, m \text{ and } j = 1, 2, \ldots, n \quad (6)$$

Where:

$$\tilde{v}_{ij} = \tilde{r}_{ij}(.)\widetilde{w}_j \quad (7)$$

It was not possible to determine a difference in weigth, with regard to each field of expertise, because there was no presumptive evidence to support this difference. Therefore, all the experts were considered to have the same weight. The weight given to each expert was: $\widetilde{w}_j = (1, 1, 1, 1, 1) \forall j \in n$. Hence, by weighting the normalized decision matrix, the matrix didn't change.

4.5.6. Positive ideal and negative ideal solution

The Fuzzy positive Ideal solution (FPIS) and the Fuzzy Negative Ideal Solution (FNIS) were calculated as follows below:

$$A_j{}^+ = (\tilde{v}_1^+, \tilde{v}_2^+, \ldots\ldots \tilde{v}_n^+)\ where\ \tilde{v}_j^+ = \max_j \{v_{ij3}\}, 1, 2, \ldots, m \text{ and n} = 1, 2, \ldots, n \qquad (8)$$

$$A_j{}^- = (\tilde{v}_1^-, \tilde{v}_2^-, \ldots\ldots \tilde{v}_n^-)\ where\ \tilde{v}_j^- = \max_j \{v_{ij3}\}, 1, 2, \ldots, m \text{ and } n = 1, 2, \ldots, n \qquad (9)$$

The sum of distances for each obstruction (D_j^+, D_j^-), from the FPIS and the FNIS, was calculated using:

$$D_j^+ = \frac{\sum_{i=1}^m d(\tilde{v}_{ij} - \tilde{v}_i^+)}{m}, j = 1, 2, \ldots, n \qquad (10)$$

And,

$$D_j^- = \frac{\sum_{i=1}^m d(\tilde{v}_{ij} - \tilde{v}_i^-)}{m}, j = 1, 2, \ldots, n \qquad (11)$$

Wherein, $d(\tilde{v}_{ij} - \tilde{v}_i^+)/d(\tilde{v}_{ij} - \tilde{v}_i^-)$ is the distance between two fuzzy numbers, that was calculated using the vector algebra. The distance between the two numbers: $A1(a_1, b_1, c_1)$ and $A2(a_2, b_2, c_2)$ was calculated as:

$$d(A1 - A2) = \sqrt{\frac{1}{3}[(a_2 - a_1)^2 + (b_2 - b_1)^2 + (c_2 - c_1)^2]} \qquad (12)$$

In supplement 8, the positive and negative distances between two fuzzy numbers, per obstruction per respondent, can be found. Appendix 3 displays the sum of the distances, negative and positive, per field of expertise.

4.5.7. The closeness coefficient

The closeness coefficient (CCj) represents the distances to the FPIS (A^+) and the FNIS (A^-) simultaneously. The CC_j value was calculated as follows:

$$CC_j = \frac{D_j^-}{(D_j^- + D_j^+)},\ j = 1, 2, \ldots, n \quad (13)$$

Thereafter, the obstructions were arranged based on the CC_j ranking, from high to low. A higher value implicates a more important obstruction. Appendix 3 displays the closeness coefficient per obstruction per field of expertise.

4.5.8. Weighting and ranking the obstructions

Using the above-mentioned formulas, the overall weight and rank of the different categories were calculated. In table 11, the weight per category can be seen, wherein the highest weight represents the highest importance, and so the highest rank, determined by experts. A visual representation is displayed in figure 11. It can be seen that the CCj value (weight) of the categories are relatively close to each other. The CCj value of the highest rank (1) is 0,5982, and of the lowest rank (7) is 0,4719. What gives a difference in CCj value of only 0,1263 between rank 1 and 7. However, it can be seen that the experts find the category Informational (C3) most important, followed by the category Economical (C4) and category Communicational (C2) least important, when it concerns the implementation of AR in the construction industry.

Table 11, Results per category

Results per category (all fields)		
Category	**CCj**	**Rank**
C1: Organizational	0.5626	**3**
C2: Communicational	0.4719	**7**
C3: Informational	0.5982	**1**
C4: Economical	0.5842	**2**
C5: Technological	0.5032	**6**
C6: Awareness	0.5284	**5**
C7: Operational	0.5490	**4**

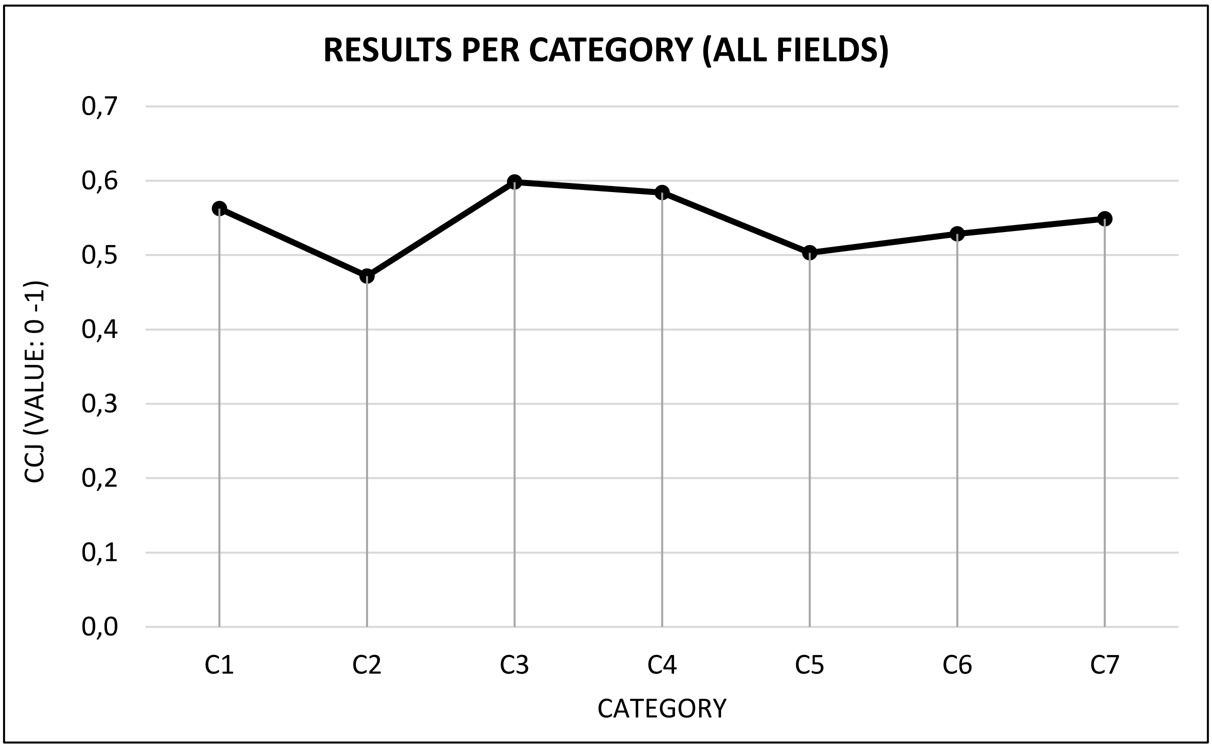

Figure 11, Results per category (all fields)

To include the difference in importance (CCj value) between the categories, the obstructions were weighted. This was done by multiplying the induvial weights by the weight of the category to which the respective obstruction is part. Table 12 displays the category in column 1, to which the obstruction in column 2 is part. In columns 3 and 4 the normal CCj value and corresponding rank can be seen. In the last two columns, the weighted variant of the weighted CCj value and corresponding rank is displayed. A visual representation can be found in figure 12. From this point on, the weighted CCj value is used for further analysis.

The change that this entails is logically greater in the most important categories (C3 and C4) and in the least important categories (C2 and Technological (C5)). This can clearly be seen in the shift of CCj value and rank, between the normal columns (3 and 4) weighted columns (5 and 6).

Looking at table 12, three highest-ranked obstructions are: (1) Poor information management (IN2: 0,3948), (2) Invisibility of added value (EC1: 0,3935) and (3) Uncertainty about Return on Investment (EC5: 0,3903). What stands out is that the highest-ranked obstructions are within the highest-ranked categories, Informational (C3) and Economical (C4). Further, the above mentioned top 3 is formed by the weighting. Initially, IN2 was ranked place 4, and after weighting increased in the ranking to place 1, EC1 decreased from 1 to rank 2, and EC5 decreases from 2 to rank 3.

Other important obstruction (outliners) worth mentioning are conservative nature of the construction industry (OR1: 0,3646), problems integrating/matching AR in current processes (OR9: 0,3663), fragmentation of knowledge (IN3: 0,3544), lack of commitment to support the information source/model (IN5: 0,3776) and ruggedness issues - making hardware compliant with safety standards (OP6: 0,3661). Besides the two most important categories, the category Organizational can also be seen as important, considering that two other important obstructions, ranked positions 4 and 5, are within this category. These are the obstructions, lack of commitment to support the information model (IN5), and problems integrating/matching AR in current processes OR(9).

Looking at the least important obstructions, quickly leads to category C2. This is the least important category, so as expected includes some of the lowest-ranked obstructions. Including the two lowest-ranked obstructions: (40) no clear definition of AR (CO3: 0,1997) and (41) afraid of the controlling function (CO2: 0,1792).

Table 12, Results per obstruction (all fields)

Results per obstruction (all fields)					
Category	**Obstructions**	**CCj**	**Rank**	**CCj W.**	**Rank W.**
C1:	**OR1**	0.6481	6	0.3646	7
	OR2	0.6068	9	0.3414	10
	OR3	0.5913	13	0.3327	12
	OR4	0.4953	32	0.2786	26
	OR5	0.5130	26	0.2886	22
	OR6	0.5886	14	0.3312	13
	OR7	0.4651	34	0.2617	30
	OR8	0.5037	31	0.2834	23
	OR9	0.6512	5	0.3663	5
C2:	**CO1**	0.5309	23	0.2505	34
	CO2	0.3797	41	0.1792	41
	CO3	0.4232	39	0.1997	40
	CO4	0.5538	21	0.2613	31
C3:	**IN1**	0.5733	17	0.3430	9
	IN2	0.6599	4	0.3948	1
	IN3	0.5924	11	0.3544	8
	IN4	0.5342	22	0.3196	17
	IN5	0.6312	8	0.3776	4
C4:	**EC1**	0.6736	1	0.3935	2
	EC2	0.5717	18	0.3339	11
	EC3	0.4508	36	0.2633	29
	EC4	0.5567	20	0.3252	14
	EC5	0.6682	2	0.3903	3
C5:	**TE1**	0.6360	7	0.3201	16
	TE2	0.5042	30	0.2537	33
	TE3	0.4629	35	0.2329	37
	TE4	0.5067	28	0.2550	32
	TE5	0.4664	33	0.2347	36
	TE6	0.4431	37	0.2230	38
C6:	**AW1**	0.5303	24	0.2802	25
	AW2	0.3829	40	0.2023	39
	AW3	0.5192	25	0.2744	28
	AW4	0.5999	10	0.3170	19
	AW5	0.5755	16	0.3041	20
	AW6	0.5627	19	0.2973	21
C7:	**OP1**	0.5048	29	0.2771	27
	OP2	0.4371	38	0.2399	35
	OP3	0.5128	27	0.2816	24
	OP4	0.5812	15	0.3191	18
	OP5	0.5915	12	0.3247	15
	OP6	0.6668	3	0.3661	6

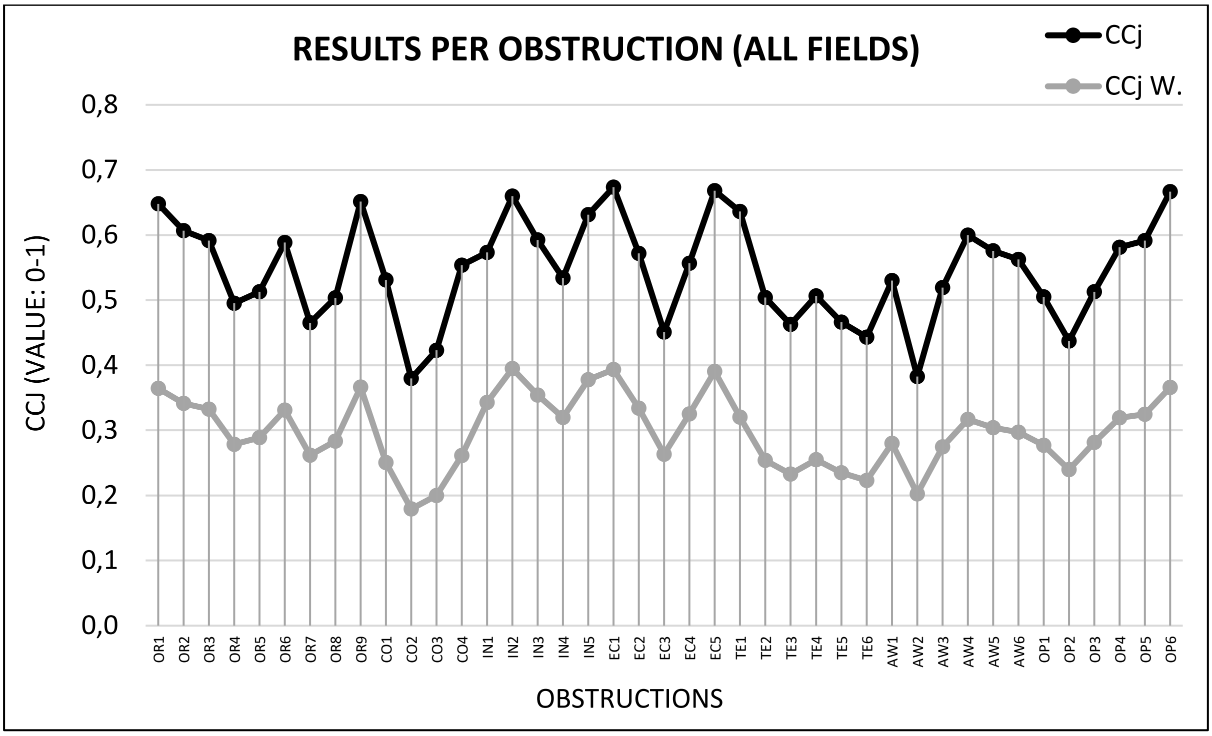

Figure 12, Results per obstruction (all fields)

4.6. Triangulation of the survey

This subchapter discusses the similarities and differences in opinion between the three distinguished fields of expertise. These fields are, as mentioned in chapter 4.5.3., Consultancy/Engineering Bureaus (construction-related), Contractors (construction-related), and Industry (not construction-related). To see the similarities and differences between them, the normal (column: 2, 6, and 10) and weighted (column: 4, 8, and 12) CCj value was calculated per field of expertise. Column 3, 5, 7, 9, 11, and 13, contain the corresponding normal and weighted ranks. These values are displayed in table 13. Because the weighted CCj value is leading in this report, only this value per field of expertise is graphically displayed in figure 13.

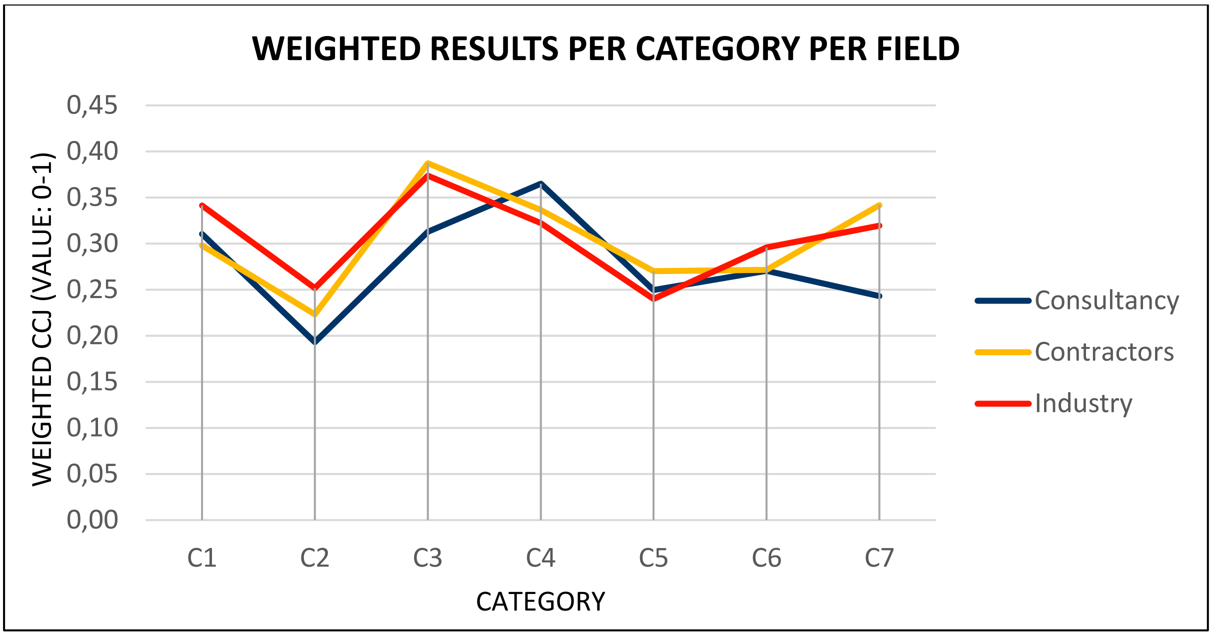

Figure 13, Weighted results per category per field

Table 13, Results per field per category

Results per category per field												
Category	**Consultancy**	**Rank**	**Consultancy W.**	**Rank W.**	**Contractors**	**Rank**	**Contractors W.**	**Rank W.**	**Industry**	**Rank**	**Industry W.**	**Rank W.**
C1	0.5517	**2**	0.3104	**3**	0.5293	**5**	0.2978	**4**	0.6068	**2**	0.3414	**2**
C2	0.4091	**7**	0.1930	**7**	0.4731	**7**	0.2232	**7**	0.5335	**6**	0.2518	**6**
C3	0.5228	**3**	0.3127	**2**	0.6472	**1**	0.3872	**1**	0.6247	**1**	0.3737	**1**
C4	0.6247	**1**	0.3650	**1**	0.5762	**3**	0.3366	**3**	0.5516	**5**	0.3222	**3**
C5	0.4959	**5**	0.2496	**5**	0.5369	**4**	0.2702	**6**	0.4768	**7**	0.2399	**7**
C6	0.5121	**4**	0.2706	**4**	0.5136	**6**	0.2714	**5**	0.5595	**4**	0.2957	**5**
C7	0.4428	**6**	0.2431	**6**	0.6224	**2**	0.3417	**2**	0.5819	**3**	0.3194	**4**

First, it needs to be mentioned that there are some minor changes between the normal and weighted CCj value, and so in the corresponding ranking. Some categories concerning the field of expertise stay the same and some change, with a maximum of two ranks. The most important and least important category stays the same, for every field of expertise, after weighting the CCj value.

For the contractors and industry (not construction-related), the most important category is Informational (C3). For the experts from consultancy bureaus that is Economical (C4), and Informational (C3) comes second. Striking is that the category operational (C7) is ranked very high by experts from contractors and industrial organizations and much lower by experts from consultancy bureaus. Because the consultancy bureaus are construction related and the industry (in this report) is independent of the construction industry. For the fields Consultancy and Contractors, the category communicational (C2) is the least important. The experts from the industrial organizations, also find this a less important category (second least important). But find the category technological even less important.

It is within the expectation pattern that Consultancy Bureaus are less in line regarding their opinion relative to contractors, then the experts from Industrial organizations, even though they are not construction related. That is because, both Contractors and the Industry are production industries (they both make something), Consultancy produces nothing tangible but only provides services.

In table 14, the CCj value and rank (normal and weighted) were calculated per obstruction per field of expertise. Again, because the weighted CCj value is leading in this report, only this value per obstruction per field of expertise is graphically displayed in figure 14. The first column of table 14 indicates the category for the obstructions in column 2. Column 3, 7, and 11 contain the normal CCj value and columns 4, 8, and 12 the corresponding ranks. In columns 5, 9, and 13, the weighted values can be found, for which columns 6, 10, and 14 contain the weighted rank.

Again, there can be seen some changes per field of expertise between the normal and weighted CCj value, and so in the corresponding ranking. Some obstructions change in rank by weighting them; others don't. The maximum in change is ten ranks; this regards category C5 obstruction TE1. Concerning the top 3 most important obstructions, obstruction IN2 increases in rank for all fields after weighting. The same goes for obstruction EC1 and EC5, due to the relatively larger weights of the categories Informational and Economical.

Table 14, results per field of expertise per obstruction

Resuls per obstruction per field of expertise													
Category	**Obstructions**	**Consultancy**	**Rank**	**Consultancy W.**	**Rank W.**	**Contractors**	**Rank**	**Constractors W.**	**Rank W.**	**Industry**	**Rank**	**Industry W.**	**Rank W.**
C1:	**OR1**	0.6499	**3**	0.3656	**3**	0.5254	**26**	0.2956	**21**	0.7691	**1**	0.4327	**1**
	OR2	0.5404	**17**	0.3040	**15**	0.5944	**14**	0.3344	**15**	0.6856	**8**	0.3857	**9**
	OR3	0.5866	**6**	0.3300	**7**	0.5005	**29**	0.2816	**26**	0.6869	**7**	0.3865	**8**
	OR4	0.5501	**14**	0.3095	**14**	0.5600	**19**	0.3150	**17**	0.3757	**39**	0.2114	**36**
	OR5	0.5750	**10**	0.3235	**10**	0.4756	**32**	0.2676	**28**	0.4885	**30**	0.2748	**27**
	OR6	0.5274	**21**	0.2967	**16**	0.5103	**28**	0.2871	**24**	0.7282	**3**	0.4097	**4**
	OR7	0.4585	**29**	0.2579	**28**	0.4066	**37**	0.2287	**36**	0.5303	**26**	0.2984	**23**
	OR8	0.5147	**25**	0.2895	**19**	0.4660	**33**	0.2622	**32**	0.5303	**26**	0.2984	**23**
	OR9	0.5627	**13**	0.3166	**11**	0.7246	**5**	0.4076	**6**	0.6662	**9**	0.3748	**12**
C2:	**CO1**	0.4408	**36**	0.2080	**38**	0.5797	**15**	0.2736	**27**	0.5723	**20**	0.2700	**29**
	CO2	0.2855	**41**	0.1347	**41**	0.4066	**37**	0.1919	**39**	0.4470	**35**	0.2109	**37**
	CO3	0.4531	**32**	0.2138	**37**	0.3460	**40**	0.1633	**40**	0.4705	**32**	0.2220	**34**
	CO4	0.4570	**30**	0.2156	**35**	0.5600	**20**	0.2643	**31**	0.6443	**14**	0.3041	**22**
C3:	**IN1**	0.4948	**26**	0.2960	**17**	0.5693	**18**	0.3406	**14**	0.6559	**11**	0.3924	**6**
	IN2	0.5912	**5**	0.3537	**4**	0.7327	**4**	0.4383	**2**	0.6559	**11**	0.3924	**6**
	IN3	0.5283	**20**	0.3160	**13**	0.6047	**11**	0.3617	**7**	0.6443	**14**	0.3855	**10**
	IN4	0.4558	**31**	0.2727	**27**	0.6047	**12**	0.3617	**8**	0.5421	**25**	0.3243	**19**
	IN5	0.5438	**16**	0.3253	**9**	0.7246	**5**	0.4335	**3**	0.6253	**17**	0.3740	**13**
C4:	**EC1**	0.6982	**1**	0.4079	**1**	0.7507	**2**	0.4386	**1**	0.5717	**22**	0.3340	**18**
	EC2	0.5827	**8**	0.3404	**6**	0.5600	**20**	0.3271	**16**	0.5723	**20**	0.3343	**17**
	EC3	0.5863	**7**	0.3425	**5**	0.4313	**35**	0.2519	**34**	0.3347	**40**	0.1955	**38**
	EC4	0.5630	**12**	0.3289	**8**	0.5350	**24**	0.3125	**19**	0.5723	**19**	0.3343	**16**
	EC5	0.6935	**2**	0.4052	**2**	0.6040	**13**	0.3529	**10**	0.7069	**6**	0.4130	**3**
C5:	**TE1**	0.5746	**11**	0.2891	**21**	0.6892	**7**	0.3468	**11**	0.6443	**14**	0.3243	**20**
	TE2	0.4748	**27**	0.2389	**30**	0.5254	**26**	0.2644	**30**	0.5124	**28**	0.2578	**30**
	TE3	0.5801	**9**	0.2919	**18**	0.4213	**36**	0.2120	**37**	0.3873	**36**	0.1949	**39**
	TE4	0.4436	**35**	0.2232	**34**	0.6892	**7**	0.3468	**11**	0.3873	**36**	0.1949	**39**
	TE5	0.4497	**34**	0.2263	**33**	0.4906	**31**	0.2469	**35**	0.4589	**34**	0.2309	**33**
	TE6	0.4527	**33**	0.2278	**31**	0.4060	**39**	0.2043	**38**	0.4707	**31**	0.2368	**32**
C6:	**AW1**	0.5478	**15**	0.2895	**20**	0.5005	**30**	0.2645	**29**	0.5426	**23**	0.2867	**25**
	AW2	0.3302	**40**	0.1745	**40**	0.2763	**41**	0.1460	**41**	0.5422	**24**	0.2865	**26**
	AW3	0.5988	**4**	0.3164	**12**	0.6549	**10**	0.3461	**13**	0.3039	**41**	0.1606	**41**
	AW4	0.5363	**18**	0.2834	**24**	0.5352	**23**	0.2828	**25**	0.7282	**3**	0.3848	**11**
	AW5	0.5254	**22**	0.2776	**26**	0.5452	**22**	0.2881	**23**	0.6559	**11**	0.3466	**15**
	AW6	0.5340	**19**	0.2822	**25**	0.5697	**16**	0.3011	**20**	0.5843	**18**	0.3088	**21**
C7:	**OP1**	0.5204	**24**	0.2857	**23**	0.5350	**24**	0.2937	**22**	0.4589	**33**	0.2520	**31**
	OP2	0.3449	**39**	0.1893	**39**	0.4658	**34**	0.2557	**33**	0.5005	**29**	0.2748	**28**
	OP3	0.3926	**38**	0.2155	**36**	0.7586	**1**	0.4165	**4**	0.3873	**36**	0.2126	**35**
	OP4	0.4146	**37**	0.2276	**32**	0.5693	**17**	0.3126	**18**	0.7597	**2**	0.4171	**2**
	OP5	0.4629	**28**	0.2541	**29**	0.6549	**9**	0.3595	**9**	0.6566	**10**	0.3605	**14**
	OP6	0.5214	**23**	0.2862	**22**	0.7507	**2**	0.4122	**5**	0.7282	**3**	0.3998	**5**

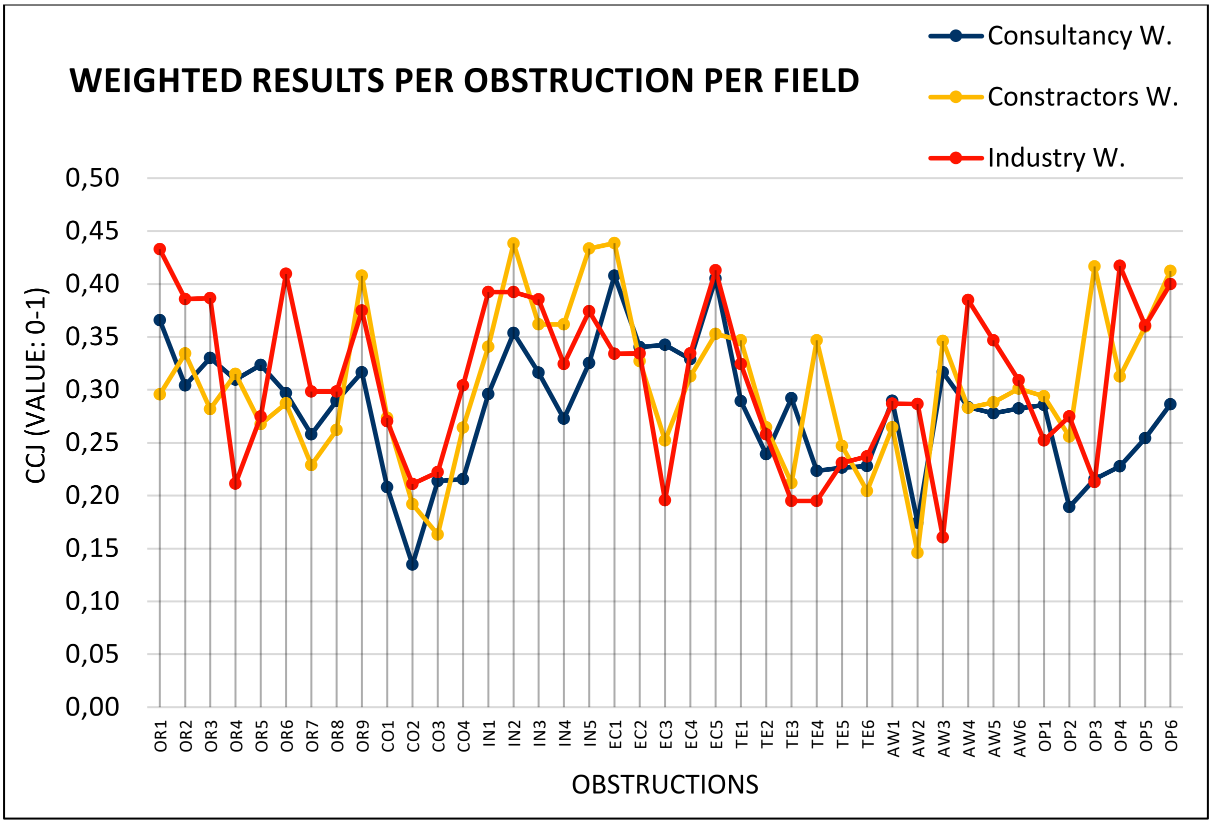

Figure 14, weighted results per obstruction per field of expertise

Investigating the weighted CCj value of all the fields of expertise separately, gives the insight that there're only few obstructions rated very similar by the experts from different fields of expertise. These obstructions are OR8, EC2, EC4, TE2, TE5, and AW1. Meaning that opinion between fields differs considerably.

Concerning the three most important obstructions, for IN2 goes that the score is relatively high, looking at each field of expertise separately. However, between the different fields, there is some difference in valuation (weight) of the obstruction present. But the ranking is quite similar, contractors appraise the obstruction for rank 2, Consultancy ranks it place 4 for, and Industry ranks it place 6. Obstruction EC1 is ranked 1st place by the fields Consultancy and Contractors, but is ranked 18th by Industry. Concerning this obstruction, also quite some weight difference is present. The 3rd most important obstruction EC5, is quite similar evaluated by Consultancy (ranked 2th) and Industry (ranked 3rd). However, Contractors have ranked the obstruction 13th place. Hence, there is some quite valuating difference in the weighted CCj value between the fields of expertise. While the valuating, and so the ranking, is proportionally even within each field of expertise in relation to each other. Two outliners downwards are found, namely the valuation of EC1 by the Industry and EC5 by the Contractors.

There are also some obstructions with a unique difference between the fields of expertise. The first one is OR1, ranked 3rd and 1st by Consultancy and Industry, but ranked 21th by Contractors. The second one is EC3; Consultancy ranks this obstruction 5th most important. On the other hand, Contractors give the obstruction a 34th place and Industry a 38th. Third, obstruction OP4 also shows a big difference between the different fields. Consultancy ranks the obstruction 32nd place, Contractors rank it 18th place, and Industry ranks it 2nd place. These relative large differences in the ranking, go hand in hand with a reasonably large difference in weight of the CCj value between the fields expertise.

As of last, the most important individual outliners are discussed. In regard to obstruction OR4, it can be seen that the weighed CCj value given by the Industry (ranked 36th) is much lower, than the given value by the Consultancy Bureaus (ranked it 14th) and Contractors (ranked it 19th), which are almost similar to each other. In regard to the ranking, the same pattern can be seen: an outliner by the field of expertise; Industry. With obstruction OR6, it's the other way around. In this case, the weighted CCj value of Industry has an outliner upwards; this also goes for the ranking. Industry ranks the obstruction 4th place. While Consultancy ranks OR6 16th place and Contractors rank the obstruction 24th place. Then, with regard to EC3, there is a big difference in the weighted CCj value and rank appraised by Consultancy (ranked it 5th) versus the more similar weighting by the Contractors (ranked it 34th) and Industry (ranked it 38th). A spike in the weighted CCj value and rank, in the valuation of obstruction TE4 by Contractors (ranked 11th), can be seen. Relative to the weight and rank given by the Consultancy (ranked it 34th) and Industry (ranked it 39th). Looking at AW2, the CCj value and ranking by the Industry is much higher than the other two fields. Industry places the obstruction 26th place, while the other two fields of expertise rank the AW2 much lower. Also, Industry assesses the obstruction mentionable higher in relation to the other fields. Further, an outliner from the Contractors field can be seen for OP3. They appraised and ranked the obstruction 4th, much higher than Consultancy (ranked it 36th) and Industry (ranked it 35th). The last considerable individual difference can be seen regarding obstruction OP6. The Consultancy Bureaus valuated this obstruction much lower in weight and rank (22nd), relative to the fields Contractors and Industry. Who ranked the obstruction 5th place. Above, both the weighted CCj value and ranking are both discussed. Because, the ranking is relative to the weighted CCj value per field of expertise (table 14 and figure 14).

Results

In this section, the findings from the analyses are reported.

5. Results

In chapter 4, the analysis, all the results were identified. This chapter discusses the most important obstructions and notable points per category from the main (GTA) and secondary (Fuzzy TOPSIS method) analyses. But first the answer concerning the third research question, is specified.

5.1. Phases of interest

Looking at the interviews, providing a supplement regarding the phases of interest concerning the implementation of AR (chapter 2.5), it stands out that experts confirm the added value for AR in almost all the stages of interest (see figure 7) that were derived from the literature research. Only phase 2, draw up project brief, is found debatable. Some experts believe that AR is of added value in all the 5 phases (Baas, 2019; Smits, 2019). According to other interviewed experts, there is no direct added value for AR in this phase. In their view, VR is cheaper, better, and easier applicable in drawing up the project brief (Zijde, 2019; Hardeveld, 2019; Ginneken, 2019). Hence, the evident stages of interest concerning the implementation of AR are:

- (3) Development of delivery strategy
- (4) Draw up design brief
- (5) Actual construction
- (6) Operate and maintain

Where the added value is (among other things) in, (3): in the development of a delivery strategy, when the basic requirements and or basic design is known, it's possible to take the customer to a location, show the options and ultimately also to place, remove and change them. (4): Use-cases have shown that within engineering concerning standardization, AR is of great added value and leads to a more efficient way of working (Steege, 2019)). So, AR is already proving it's added value in fixed, repetitive processes. In addition, also in construction (5), in which it ensures better communication, visualization detailing, and optimizing other processes within design and engineering (Oldenhave, 2019; Steege, 2019). However, it's debatable whether the current added value within actual construction is high enough. A good example was given by Olden have: "If the only argument is having your hands free, then a screen on the wall will do" (Oldenhave, 2019). So for usage in construction, the case must be better. The current versions, for example workflow visualization, are still too limited. This can, and approximately will improve over time. Think of improving object recognition and enhancing the connection to backend systems. (6): BIM models play a major role in the operation and maintenance phase; therefore, AR can already have an impact. For example, it's always possible to use it for asset management in a completed building. Think of the ability to know where the pipes run and the smart smoke detectors are located.

So, it all starts with the structuring of data because everything that is send or streamed to an AR device must go from a certain data structure to an AR-device. It starts in the design phase with ensuring that this structure of data is in order, that it contains the correct information, and making sure that it's available (including the right content, format, and structure) at a later stage. Often it's challenging to get the right information, for example, renovation projects wherein initially no 3D models were used and so often not all the required data is present.

Regarding all the phases of interest, there isn't much room for experimentation in construction. An object is only built once, and therefore must be constructed the first time right. The AR technique can help to support this process.

5.2. Results of the analyses

In this subchapter, the results of the main analyses, in combination with secondary analyses, are discussed. With an emphasis on the most important obstructions and highlights from the main analyses, described within a practical context, using the seven distinguished categories as a guideline.

5.2.1. The most important barriers

In table 15, the result (weighted) per obstruction, for all fields of expertise combined can be seen and is displayed graphically in figure 15. Looking at the most important obstructions, it can be seen that the top 3 most important obstructions (circled in figure 15) are within the previously mentioned two most important categories; Informational (C3) and Financial/Economical (C4).

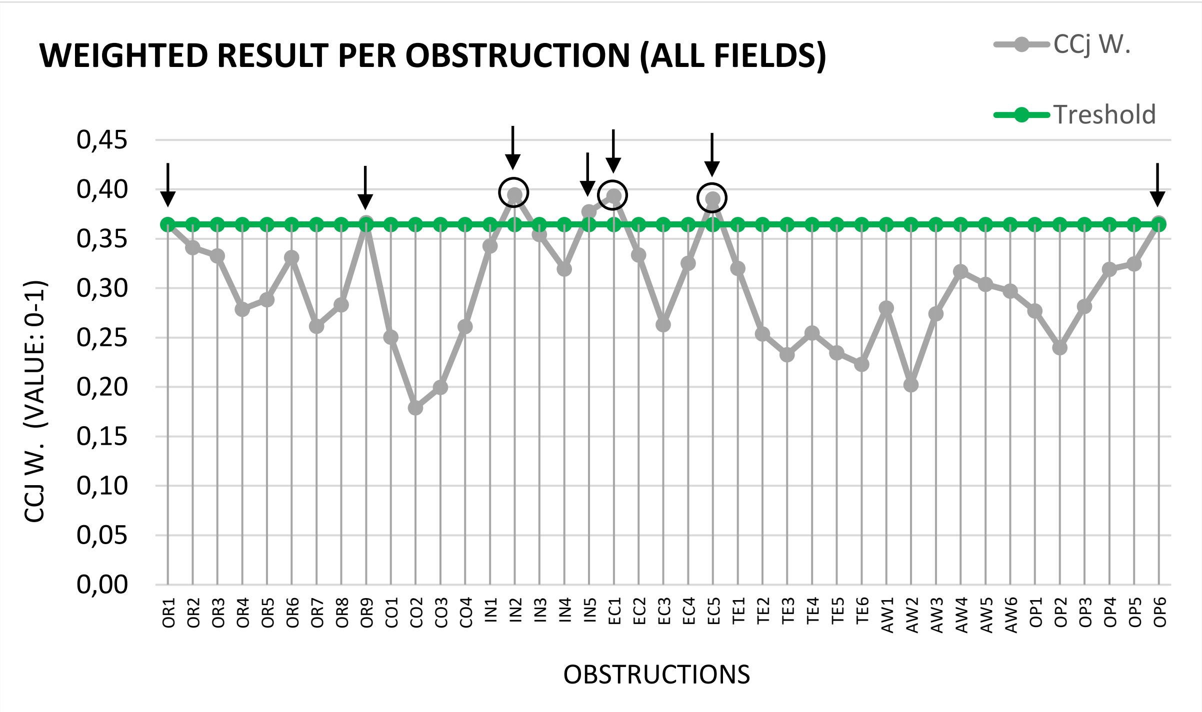

Figure 15, Threshold for weighted results per obstruction (all fields of expertise)

These three most important obstructions, indicated in chapter 4.5.8., are shown again below for clarity.

- IN2: Poor information management
- EC1: Invisibility of added value
- EC5: Uncertainty about Return on Investment

Because these are also within the two most important categories, they are used as a starting point for giving direction to the main question in the conclusion. Based on the enablers, a practical solution on how to possibly overcome the three most important obstructions, is provided.

When using the Fuzzy TOPSIS method, the 80/20 rule can be used for establishing a threshold value for determining the most important obstructions. The rule indicates that among the obstructions, "20% of the factors account for an 80% degree of importance of all the factors" (Kuo & Chen, 2008). So, 80% of the results can be described by 20% of the obstructions. Looking at table 12, the total weighted CCj value for al obstructions is 12.2380, setting the threshold value at $\alpha = 0.20$ * 12.2380 = 2,4476. This means that the combined weighted CCj values of the highest-ranked obstructions (high to low) have to account for this number. The threshold value was achieved by adding up the weighted CCj values of the seven highest-ranked obstructions., setting the definite threshold at $\alpha =$ 2,6532 (table 15). These seven obstructions can be found in table 15 and are displayed in figure 15 by an arrow. These obstructions are discussed in the following chapter.

Table 15, General most important obstructions

Most important obstructions in general (weighting considers all fields of expertise)				
Category	**Code**	**Obstructions**	**Weight**	**Rank**
C1	**OR1**	Conservative nature of the construction industry	0,3646	7
	OR9	Problems integrating/matching AR in current processes	0,3663	5
C3	**IN2**	Poor information management	0,3948	1
	IN5	Lack of commitment to support the information model	0,3776	4
C4	**EC1**	Invisibility of added value	0,3935	2
	EC5	Uncertainty about Return on Investment (RoI)	0,3903	3
C7	**OP6**	Ruggedness issues, making hardware compliant with safety standards	0,3661	6
Total			**2.6532**	**7**

5.2.2. Towards a pattern

In this sub-chapter, the highlights of the analyses are discussed, with emphasis on the seven most important obstructions (chapter 5.2.1.) and the most important aspects of the main analysis, using the categories as a guideline.

Organizational

Looking at the category Organizational, the most important aspects can be discussed using the terms conservative nature, connection with the current processes, and no concrete strategy concerning AR (figure 16). In comparison with other sectors, for example the high-tech sector, the construction industry is still lagging behind when it comes to innovation. Other sectors are more inclined to try to innovate or try new technologies and actually to implement them if they succeed. New technologies as AR, VR, and Digital Twins are currently only used as means to create a USP (Unique Selling Point(s)) relative to other parties. Not to improve their own business processes, as a result of which the technology cannot reach its full potential.

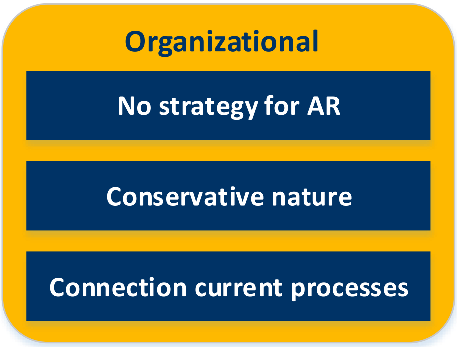

Figure 16, Highlights category "Organizational"

A distinction can be made between project organizations and departments that focus especially on new technologies. These departments really try to get AR of the ground (exploring the possibilities/applications and developing the AR technology). In contrast to the above-mentioned project organizations, that are often still very cumbersome, stuck in their old habits, and reluctant to change.

The lack of a central vision and company strategy on AR is partly responsible for maintaining the conservative way of thinking concerning new technologies, including AR. There is no central vision and or set objectives regarding AR, often only some small scale experiments on project level. However, there are objectives with regard to the digitalization of construction. But these are most of the time abstract and do not address AR specifically. So there are various parties within the construction industry who are willing to try and use the technology but miss the sustainable strategy as a foundation to support the technology — making the adoption of AR going in a sluggish phase.

To use AR for supporting or optimizing business processes, involved employees have to learn how the AR technique of concern works. Due to the conservative nature of the industry, employees are often reluctant to put in this effort. Because in their perception, the old tricks do the job just fine, so why change. Also, the AR technology has to be aligned with the current processes in order to be part of the business operations. Here too, time and energy must be invested, and a certain degree of flexibility is demanded. Again, this is very difficult to achieve because of the conservative attitude of many people in the construction industry.

Chapter 5.2.4. describes the notable possible benefits of using AR in the construction industry, providing insight into why AR can be beneficial.

(Oldenhave, 2019; Ginneken, 2019; Zijde, 2019; Hardeveld, 2019; Steege, 2019; Baas, 2019; Smits, 2019)

Communicational

The key aspects of the category Communicational can be referred to as no clear definition of AR and, wrong expectations (figure 17). Al experts agree on the fact that AR is an overlay on reality that offers added value. But from there, the dividing line between similar technologies, such as VR and MR, becomes vague. This makes it difficult to grasp what AR exactly means. Especially for people that not specialize in such technologies.

Figure 17, Highlights category "Communicational"

Often organizations advertise with AR cases and applications they can't actually deliver. They use AR almost purely for marketing and or conviction (for example, more budget) and for that purpose, overpromise. Creating wrong or unrealistic expectations (for AR), fed by the lack of clarity regarding the definition of AR.

(Oldenhave, 2019; Ginneken, 2019; Zijde, 2019; Hardeveld, 2019; Steege, 2019; Baas, 2019; Smits, 2019)

Informational

Thirdly, the category Informational is discussed using the most important aspects of the category: fragmentation of knowledge, lack of commitment to support the information model (data structure) and, poor information management (figure 18).

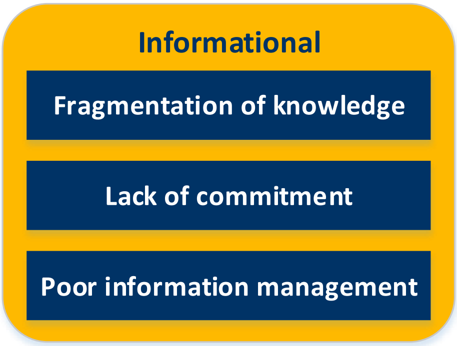

Figure 18, Highlights category "Informational"

Organizations within the construction industry are often large companies (contractors), necessary to deal (have enough resources) with large projects. For that purpose, frequently, a separate organization/team within the company is formed for each project. People "hired" for such a project, by the project organization, often spread to other project teams after completion. Not keeping the team together makes it impossible to build on the successful experiences from previous projects (as a team). This means that knowledge is fragmented and spreads throughout the company, losing a lot of knowledge. Meaning that the knowledge must be transferred again to other people, that do not have the experience, in a different team. This makes it very difficult to get the AR technology up and running within a company. Also, when experts leave, (a part of) the knowledge is gone, causing the technology to stagnate or potentially bleed to death. Hence, AR is something that needs to be founded in the organization and not something that only belongs to a few experts. Another problem caused by fragmentation is that it makes it hard to determine the added value of the technology. The category Economical elaborates further on the added value. The above-mentioned fragmentation of knowledge is partly a result of poor information management, which inhibits knowledge transfer.

The construction industry has a lot of information at its disposal. By making the link between structured data and the AR technology, expectably the industry will be able to display lots of information visually. Information management concerning AR starts with structured data and the industry agreements/standards that facilitate this data. Wherein, the most important aspect is: having the data structure in the right state. By right state, the condition where the structure is ready for AR use, is meant. This is a big challenge due to the lack of support for these structures, because there are no set standards and the agreed-upon standards (for example, BIM protocol) are not being maintained or are interpreted differently. Let's take BIM models as an example, because they are very often used in the Dutch construction industry. A lot of times, these models aren't structured accordingly to the BIM protocol or even to the necessary level for adequate functioning during a project. Let alone that the model has been arranged correctly for AR purposes, which means the right classification of classes and objects so that the model can be converted and subsequently processed by an AR device. Think of two different parties who work on a project, for which they use BIM. When one party has finished their part of the project, often an incomplete model is forwarded to the second party. An incomplete model refers to a model that doesn't contain all the necessary information, the right structuring of information and or the correct information. As a result, the model is too "heavy" or incomplete and not compliant with AR devices. These kinds of situations are caused by the lack of vision from parent parties, usually clients and or main contractors. Because no standards are set, parent parties fail to maintain the agreed standard and or the lack to support the information model (data structure) by the involved parties.

An important development is Rijkswaterstaat (the Dutch Road Authority) going to demand a Digital Twin of each new "Kunstwerk" (special pieces of roadworks, a viaduct for example) . All the information and all the changes regarding a "Kunstwerk", needs to be recorded digitally. In order to make this work and for AR in general, it's very important that all changes and all information are recorded proportionally to the construction cycle. This isn't happing well at the moment, causing problems as described in the last section. Therefore, an important obstructions that information management faces. Another problem is that, due to insufficient data and model standardization, a digital twin is not yet defined by Rijkswatersstaat. It's therefore not clear what to expect, and which information and preconditions apply to the models.

Lastly, an important aspect to mention is that currently the information concerning AR, most of the time, isn't centrally visibly and device-independent. Which is at the expense of broad employability of AR and access to information. Another major obstruction for information management to tackle.

(Oldenhave, 2019; Ginneken, 2019; Zijde, 2019; Hardeveld, 2019; Steege, 2019; Baas, 2019; Smits, 2019)

Economical

In the category Economical, the most important aspects are indicated as the invisibility of added value, uncertainty about RoI, and the project-based funding of works (figure 19).

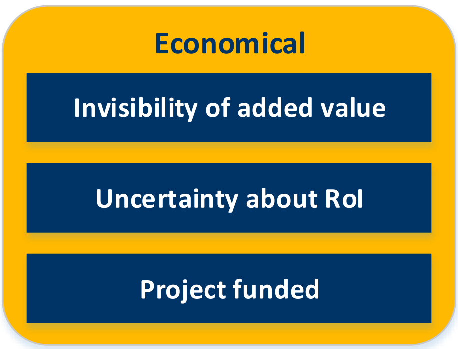

Figure 19, Highlights category "Economical"

Unfortunately, a short investment horizon isn't uncommon in the construction industry. This makes it difficult to instigate new investments, because profits must be made on project, margins must remain or increase, and extras are unfortunate always at the expense of the margins. One of the biggest obstructions are the limited innovation budgets. Generally, these budgets aren't sufficiently organization-wide controlled. This means that investments have to be made by the project organization. Herein, a big difference with other sectors can be seen. For example, the production industry, in contrast to the construction industry, uses product thinking instead of project thinking. Usually, funding the standardization of products from a central innovation budget versus the usual project funded works of the construction industry.

Certainly, when there is a desire to apply AR directly in a project, at which the project manager is responsible for the project budget, there is little willingness. Because AR is only currently becoming applicable, and first-time implementations are, risk increasing, cost extra time, require a larger investment, and often don't deliver direct added value. The prospects for AR being beneficial in projects are good (see 5.2.4.), but due to the lack of use-cases (category Awareness discusses use-cases), it's currently not possible to pass judgment on this. Therefore only a very few companies a project ultimately allow it to be tried. Let alone implement it as a company standard. These companies are often larger contractors that see future in the technology and hire consultancy bureaus to find useful applications together. Unfortunately, it often stops there, because the next step, including AR in the business processes, experiences multiple obstructions (table 7). Making the technology linger in the initial phase.

Also, there is still quite a lot of ignorance about the AR technology. For small companies, it concerns large amounts of money, which they, in many cases, can't afford or for which they consider the risk of investment (still) to great (certainly when it involves a proof-of-concept).

This is closely related to the invisibility of the added value. A few large contractors are currently including AR in their projects. Usually, AR is included in the quotation, or a project manager indicates that he or she sees added value in the use of AR within the project. But as before mentioned, not as such that it's also already included in the scope. It often gets stuck on the costs of working out a project-specific AR application. Nowadays, a lot of development costs are involved in the development of new applicable technologies. As a result, the development is abolished, because the added value isn't sufficiently visible or not (immediately) high enough.

As already said, construction remains a traditional industry, making it extra difficult to convince people of the added value. Without tangible proof, a large part of the industry remains skeptical about AR. Wherein, the lack of use-cases (as mentioned above) and the fact that AR is not (yet) included in tenders, do not promote insight into the added value. It's now a matter of searching for the right application and the drive to do a couple of projects, proving the concept. Wherein the yield (RoI) is properly measured, so that the added value becomes clearly justifiable and presentable. The risk currently, in the initial phase, is that in combination with phones and tablets, it will become a gimmick.

It all starts with the industry, in which the need for change must be seen. If that awareness isn't present, the application can be very good, but the story will end just as fast. The younger generation is less conservative, has already come into contact with new technologies during education, and therefore finds it easier to see the added value and will be more inclined trying to pull the new technology forward.

(Oldenhave, 2019; Ginneken, 2019; Zijde, 2019; Hardeveld, 2019; Steege, 2019; Baas, 2019; Smits, 2019)

Technological

The pattern within the category Technological can best be described by using the terms hardware limitations, unwieldy software processes, and the AR field is vast and diverse figure 20.

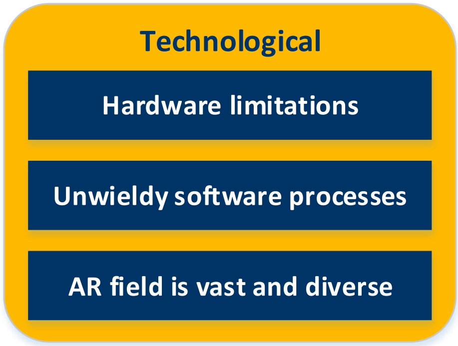

Figure 20, Highlights category "Technological"

At the moment AR devices are still impractical, think of log, little wearing comfort (partly due to size and weight), limited battery life, limited field of vision, limited computing capacity, malfunctioning in a lot of light, partly due to this having difficulty with recognizing objects, alignment problems, and calibration problems. So currently, the hardware still has some serious limitations, which are at the expense of the workability (especially in construction environments). Therefore, many construction companies find the hardware not yet good enough to include AR in their business processes.

A frequently used argument is: “the technology is not yet developed far enough, so we are not doing anything with it at the moment”. But an organization has to think about the long term strategy concerning innovative technologies, so that when the hardware is ready, the company is ready. If other companies start earlier developing the AR and see that there are useful applications for the technology, and for example, have adapted their 3D models to the new AR technology, it is very difficult for another company to catch up on this.

In regard to the applications, the software has no problem complying with precision jobs, but the hardware can only maintain a certain level of precision. There is currently only one device whose precision is reasonably good, and that is the HoloLens. Microsoft guarantees precision up to 1 centimeter. However, tests have shown that it’s possible to achieve a deviation of not more than 1 to 2 mm on a 10-meter model. This is sufficient for most scenarios, but for some applications, this still isn’t precise enough. Nor can the HoloLens process a whole BIM model (based on a normal building project) in one go. Computers often have a hard time processing/loading BIM models (not enough graphical and / or calculation capacity), let alone that the HoloLens can handle these heavy models. Because the HoloLens has much less graphic memory and computing capacity. But by dividing models into pieces and process the model piece by piece, there are already some possibilities for workable use.

Major steps are currently being taken in the development of AR hardware. In particular, the new Hololens 2 should continue to advance the technology in the field of hardware. With respect to the Hololens 1, the main improvements are a greatly increased field of vision, higher detail level, better ergonomics, lighter, longer battery life, retractable visor, improved speech command, and larger processor capacity.

When the technology is further developed, the previously mentioned problems will decrease or even disappear, and the technology will become more workable. As a result, the HoloLens and other AR devices will become more and better applicable. Already, performing some “tricks”, using software, some limitations can be minimized. For example, increasing the precision level of the HoloLens.

It can also be seen that large parties, such as Autodesk and Unity, are increasingly working together. The expectation is that the software will become more efficient in the coming years. This motivates and triggers companies to take steps. The expectation is that AR applications can be integrated within the construction process in the upcoming years.

What is seen within software applications, is that a software developer makes an AR app while possibly not even knowing how the BIM process works. So if, for example, the application works on the basis of IFC-models, it's also projected into reality-based upon this. But concerning installation technology, there are never walls and or columns, etc. present in the model. Making it impossible to export these from the IFC model, because they are simply not included. In addition, the export is done from a model, and therefore you can't export linked files. For that, a wall has to be applied in the installation model, in order to get the placement right, which is very illogical.

Also, the conversion process itself is very cumbersome. Again, an example concerning the HoloLens is given. IFC/ABS files must be converted, and then the correct information must be extracted from the converted files, so they can be exported to an AR device in order to be used. This process can only be executed by someone with IT skills and is still too cumbersome for workable use within projects and or organizations.

But the process of converting BIM models to AR is getting better and better. If you now use, for example, Revit, Unity, Pixies in combination with the new HoloLens, the converting process is already quite streamlined (Baas, 2019; Zijde, 2019). One can, without any programming knowledge, convert the BIM model to an AR model. By going through the following process,; save the Revit file, upload the file in Unity via Pixies and then select in Pixies the device one wants to stream the file to. This technology has just been released and is definitely something to take into account.

There is a wide range of hardware special for AR and hardware, not specifically for AR, but usable in combination with the technology on the market. But no device specifically designed for the construction industry, meaning no ready-made solution from a hardware point of view. Currently, as mentioned above, the HoloLens is the best usable device according to the experts

Therefore, the development of user-friendly applications that abide to the right paradigm or context awareness (discussed by the next category) and pervasiveness is an important barrier for implementing pervasive AR solutions. With the field of AR being very vast and diverse, companies need to consider developing applications specifically for the construction industry. (Silverio, Renukappa, & Sures, 2017) Herein, one of the biggest challenges is that there're (too) many possibilities with the technology. That sounds strange, but almost all activities can be visualized and or simulated. Because of this, it is often forgotten that AR is never a goal in itself, but a means of achieving a certain activity. Take the HoloLens as an example, because there are loads of applications for the device, it's difficult to keep focus and not want too much at once. What makes it difficult to choose a clear application for the technology.

(Oldenhave, 2019; Ginneken, 2019; Zijde, 2019; Hardeveld, 2019; Steege, 2019; Baas, 2019; Smits, 2019)

Awareness

The aspects unfamiliarity with AR and limited number of use cases, are best suited to describe the category Awareness (figure 21).

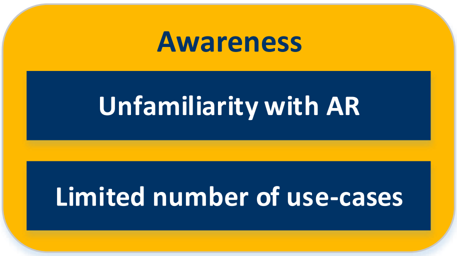

Figure 21, Highlights category "Awareness""

An obstruction in the category Awareness, is unknown makes unloved. Certainly, because as discussed above, construction is a somewhat conservative industry. People have always been doing things in a certain way for a long time and are not very eager to change that. Everyone within an organization should be familiar with AR. Unfortunately, this is currently not nearly the case. In fact, the majority within an organization is not familiar with the technology. They don't need to know all the preconditions, but must be familiar with the concept and know that it plays a role within the organization. Therefore, the industry must first become familiar with the technology in order to understand the possibilities. If the aforementioned added value can be made transparent, this will support clarifying the added value.

As already mentioned, there are still no or limited use cases for comparison within the construction industry. Due to the lack of these use cases, it's impossible to determine the exact added value. Also, without comparable use cases, it is very difficult to calculate the RoI. These cases are necessary to show everyone how it's supposed to be done, and this is what it yields. Enabling quantification of the added value, in order to convince the construction industry and ensure faster adoption.

(Oldenhave, 2019; Ginneken, 2019; Zijde, 2019; Hardeveld, 2019; Steege, 2019; Baas, 2019; Smits, 2019)

Operational

In the last category, Operational, the most important aspects are change in operational processes and the ruggedness issues with regard to making the hardware compliant with safety standards (figure 22).

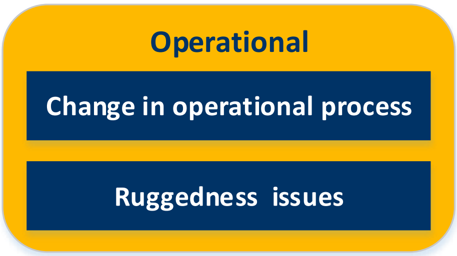

Figure 22, Highlights category "Operational"

Often the risk involved in implementing AR is considerable. As mentioned, AR only works if it's included within the business processes and not if it's seen as something additional. As a result, the technology has to enter critical processes, usually the operational processes that directly earn money for the company. The impact is therefore quite large if it goes well, but also if it goes wrong.

Regarding ruggedness issues (o.a. safety), the glasses that are now on the market, still have a (too) restrictive field of vision. Which can lead to unsafe situations, such as protruding objects that are overlooked. On the other hand, this was and is always a risk; it remains dangerous work. Operational personnel is often focused on something, which means they do not always take the environment into consideration. It's a factor that may increase the risk, but the risk is in fact already there. As stated, the hardware is currently undergoing a transition. A new generation is coming, that can take AR to a higher level. Making the work possibly even safer in the future, for example, glasses that help to recognize the dangers on the construction sites and thus prevent accidents.

Further, some operational issues are: limited battery life, poor ergonomics and portability of AR devices, poor accuracy with standard available devices, problems with positioning, workability is situation dependent, information flow doesn't run parallel to the construction process, lack of acceptance and or motivation regarding the operational employees (social acceptance), registration problems, problems with the data intake, occlusion issues, problems with the alignment between real and virtual entities, moderate quality of the displayed added dimension, afraid of controlling function, on-site connectivity problems and the limited capability of the devices for processing information

(Oldenhave, 2019; Ginneken, 2019; Zijde, 2019; Hardeveld, 2019; Steege, 2019; Baas, 2019; Smits, 2019; Calderon-Hernandez & Brioso, 2018)

5.2.3. Enablers concerning the most important obstructions

As mentioned before, the three most important obstructions are within the two most important categories: Informational and Economical. The relevant enablers, that relate to the three most important obstructions of these two categories, are used as a starting point for answering the main question in the conclusion. The relevant enablers for these categories, derived using the GTA (main analysis, see appendix 2 for all the enablers per source per category), can be found in table 16

Regarding the enablers, this chapter only looks at the enablers that make it possible to overcome the obstructions. So not to the enablers who indicate the benefits of the technique, making the technique feasible and or advantageous to use.

Table 16, Enablers categories; Informational and Economical

Enablers categories: Informational and Economical	
Informational	**Economical**
(BIM) Model information structuring	Advancing feasibility study
Information centrally visible	
Run information flow parallel to process	
Introduce universal AR protocol	

Because some enablers are the basis of other enablers (one can't function without the other) and some enablers apply to multiple categories, but are categorized based on the category that fits best (chapter 4.3.), the other categories are also considered. Including these as well allows for approaching the practical recommendation from a broader perspective. Therefore the relevant enablers (that relate the three most important obstructions) of all the other categories: Organizational, Communicational, Technological, Awareness and Operational (appendix 2), are also taken into consideration (see table 17).

Table 17, Enablers categories: Organizational, Communicational, Technological, Awareness and Operational

Enablers categories: Organizational, Communicational, Technological, Awareness, Operational	
Organizational	**Communicational**
Organization based funding	Knowledge sharing
Standardizing processes	Clear definition of AR and what AR includes
Well defined business case (organization level)	Creating trust
	Involve the decision makers
Technological	**Awareness**

Improving the hardware	Including AR in tenders by client
Device independent	Stimulate familiarity with AR
Universal software platform, convert BIM to AR	Rejuvenation in the construction industry
Modular construction of the technology	Example successful use case
Compensating hardware with software	
Operational	
Develop/introduce in small manageable steps	
Verification of simulation	

In order to choose the best enablers for a practical recommendation, regarding the first steps towards successful implementation of AR in the construction industry, looking at the three most important obstructions, there was close collaboration with the information manager of Heijmans (Robroch, 2019). Together, the above mentioned relevant enablers in table 17, were discussed. The following enablers of AR, have been found the best possible fit for giving a practical recommendation on overcoming the three most important obstructions, concerning the implementation of AR in the construction industry.

Set up an universal AR protocol

Information management concerning AR starts with structured data and the industry agreements/standards that facilitate this data. Because everything that is sent/streamed to an AR device, is based on this structured data. Wherein, the most important aspect is: having the data structure in the right state. By right state, the condition where the structure is ready for AR use, is meant. This is a big challenge due to the lack of support for these structures, because there are no set standards and the agreed-upon standards (for example, BIM protocol) are not being maintained or are interpreted differently.Further is currently the information concerning AR, most of the time, not centrally visibly and device-independent. Which is at the expense of broad employability of AR and access to information.

Introducing an AR protocol provides a guide on how to use AR technology according to a certain standard. Enables the right structuring of BIM models using the same “language,” providing applicable AR models based on the same standards. By setting a standard for both structuring models and the “language”, in an AR protocol, the management of information concerning AR technology becomes a lot less complicated. Standard structuring ensures that the data structure (for example, BIM model) can be converted device-independent (because the models are then always structured in the same way) and then be used by AR devices, without having to adjust the structure. Herein, the uniform “language” will prevent miscommunication.

Including communication and data flows in the protocol, on how the communication should take place, where the data should be stored and how the data should be stored, makes it easier to control the information flows with regard to the technology. Note these communication and data flows should be set before starting a project and maintained by information management of the responsible party. In order to prevent deviation from set agreements and thereby caused errors. By setting up a central database for storing the data, the information concerning AR will be centrally visible, facilitating broad employability of AR and easy access to the information.

Exemplary use cases

There’re still no or limited use cases for comparison within construction industry. Due to the lack of these use cases, it’s impossible to determine the exact added value. Also, without comparable use cases, it is very difficult to calculate the RoI. These cases are necessary to show the industry how it's supposed to be done, and this is what it yields. Enabling quantification of the added value in order to convince the construction industry and ensure faster adoption.

There are only a few companies within the industry needed, that show what's possible, achieve a huge saving, demonstrate that you can train people much faster and or can shorten the lead time of projects considerably, when using AR. If these companies, by using AR, take the wind out of the sails of the competition, the rest of the construction industry will most likely follow. However, the question is whether the accumulated backlog can still be caught up

By including AR within a whole project and not only partial in the form of a pilot, it will be possible determine the exact pros and cons for that type of project and associated work. By measuring the costs, time, and possible reduction of cost and time, while keeping in mind that a first-time implementation always is more time consuming and costly, an indication of the yield and RoI can be determined.

Such a use case gives insight into the usefulness of the technology in similar projects or similar works and as a reference for other (similar) projects and works. After conducting a few successful use cases, it's possible to create a standard template in the form of the above discussed AR protocol. This means that the wheel doesn't need to be reinvented every time, resulting in a more efficient AR process.

Organization based funding

This is an indirect enabler that allows for doing use cases and setting up an AR protocol. Because, as described in the previous subchapter, AR currently needs to be funded from the project budget. As a result, there is little willingness among project managers. Because the use of a new technology (for the first time) increases the risk, requires extra effort (time), and an initial investment within the project, which often does not immediately produce added value. Without willingness, the technology will not be applied. Making it senseless to apply other enablers for getting AR of the ground. Organizations based funding, therefore, forms the basis for applying the technology. That is why it has been decided to include this enabler, even though it does not directly (but indirectly) help to overcome one of the three most important obstructions.

By not financing AR of the project budget, but from a centrally created budget, it becomes much more attractive for a project manager to include AR in their project. This allows for use cases and gives the technology the opportunity to display it's added value. (Ginneken, 2019)

5.2.4. The benefits of using AR

The last subchapter discussed the enablers, that make it possible to overcome the obstructions. This subchapter looks at the enablers who indicate the benefits (added value) of the technique, making the technique feasible and or advantageous to use. These benefits are derived from the enablers in appendix 2, that originally stem from the main analysis. In table 18 below, the possible benefits per category are displayed.

Table 18, Enablers indicating added value per category

Enablers indicating added value per category	
Organizational	**Communicational**
Improved process control	Improve knowledge sharing process
Agile, allowing for fast and easy adaption	Improving stakeholder management
Coordinate way of thinking	Improving communication
Reduce mistakes and defects	Making interaction tangible
	Improve decision making process
Informational	**Economical**
Providing insight in the design	Less failure costs
Information centrally visible	Reducing consultancy costs
Traceability of work or service	Higher cost-efficiencies
Improves 4D scheduling	
Technological	**Awareness**
Allowing automated monitoring and measuring	-
Defect/error detection	
Operational	
Improving executability of difficult work	Faster maintenance interventions
Verification of simulation	Remote guidance and supervision
Digital testing/simulation	Supplement shortcomings of BIM on-site
Providing work instructions	Enabling site navigation
Better quality management	Improve safety
Enhance scheduling	Cheaper and efficient enhancing human safety
Enhance visualization	More effective and efficient training/education
Enhance progress tracking	

Looking at table 18, it can be seen that most beneficial aspects concern the operational category.

Conclusion

This chapter summarizes the main points of evidence (findings), by answering the five sub research questions.

6. Conclusion

The research objective of this study is to examine the potential of AR within the Dutch construction industry focusing on the first steps towards the successful implementation of AR and thereby wider AR adoption. To answer the main and five sub research questions, two main data sources were used: literature research and interviews. Literature research created an image of the current state and the benefits of using AR in the construction industry, answering the first two sub research questions. Additionally, document research was conducted to supplement the literature research. Which, together with the interviews, formed the qualitative research, and so the basis for the Grounded Theory Approach analysis (main analyses). Together with the previously mentioned literature research, the third research question, the stages of interest concerning the implementation of AR, could be answered. By the GTA analyses, the obstructions and enablers have been mapped. These obstructions were rated on their importance within the construction industry, by different fields of expertise concerning the AR technology, using the Fuzzy TOPSIS method. Providing a ranking of the obstructions, and so the most important obstructions and categories. Answering the last two sub-questions. The relevant enablers per category are used, in consultation with an expert, to give a practical recommendation on how to overcome the three most important obstructions in chapter 7.

6.1. The current state of AR in the construction industry

There are many uses for AR in the construction industry, whereof progress tracking is one of the most used functions. As projects becomes more complex, many scholars and researchers are looking to augmented reality to resolve the complexity of projects (Lin, Liu , Tsai , & Kang , 2014). Many researchers, like Mani Golparvar-Fard, have researched programs like D4AR and how these AR technologies are used to monitor progress on job sites (Golparvar-Fard, Peña-Mora, & Savarese, 2009).

Access to project information on-site is significantly improving with the introduction of different augmented reality (AR) programs compared to more traditional information sources (Pejoska , Bauters, Purma , & Leinonen, 2016). To reduce the difficulties for on-site information retrieval many companies are starting to develop lightweight mobile devices.

AR is still relatively in its early stages of development pertaining to the construction industry, but it is already showing great potential (Behzadi, 2016), and is deemed to be a key enabler to address the current shortcomings of BIM on-site use in construction (Wang, et al., 2013). These technologies allow construction management to address defects that might be overlooked in the inspection process and save time doing so. If managers know the core control time points and measures for works to be checked proactively through the defect domain ontology, then the worker's performance can be automatically checked at the right time with BIM and AR applied inspection tools without visiting the workplace (Park, Lee, Kwon, & Wang, 2013).

However, the construction industry struggles with the adoption of AR. Some of the main (container) obstructions that stagnate the adoption are immature core virtual reality technology, conservative nature of construction businesses, size of building information models (Meža, Turk, & Dolenc, 2015), relative high costs of AR technology, hardware issues and the scarcity of AR application specifically designed for the construction industry (Silverio, Renukappa, & Sures, 2017).

Also, several experts on AR indicate the difficult introduction of the AR technology with regard to the construction Industry (Oldenhave, 2019; Ginneken, 2019; Zijde, 2019; Hardeveld, 2019; Steege, 2019; Baas, 2019; Smits, 2019). The specific obstructions that cause the difficult introduction are discussed later on in the conclusion (subchapter 6.4).

6.2. The benefits of using AR in the construction industry

Augmented reality will improve the scheduling aspect of the construction industry greatly; it can show an as-planned vs. an as-built structure to allow visualization of progress (Zollmann, et al., 2014). Access to project information on-site is significantly improving with the introduction of different augmented reality (AR) programs compared to more traditional information sources (Pejoska , Bauters, Purma , & Leinonen, 2016). These AR systems allow fast access to information helps project managers to decide on corrective actions to minimize cost and delays due to performance discrepancies (Bae , Golparvar-Fard, & White , 2013). These new AR programs give multiple parties associated with construction projects the ability to clearly grasp the whole picture of the project site and to make accurate predictions about future activities (Lin, Liu , Tsai , & Kang , 2014). The added visualization benefits of AR technologies allow for better communication between parties when commenting and making suggestions for a particular project (Hsieh, Kang, & Lin, 2016).

In specific, if managers know the core control time points and measures for works to be checked proactively through the defect domain ontology, then the worker's performance can be automatically checked at the right time with BIM and AR applied inspection tools without visiting the workplace (Park, Lee, Kwon, & Wang, 2013). Allowing managers to save both time and money on specific projects while lowering Man-Labor hours and cost efficiencies due to defects and construction rework. Much money and time are wasted because plans or drawings are misinterpreted, or the information is transferred imprecisely from the plan to the real object (Wang, Truijens, Hou, Wang, & Zhou, 2014).

Also, by using augmented reality, the total cost of "the same knowledge that needs to be imparted with respect to safety, could be reduced dramatically" (Agrawal , Acharya , Balasubramanian, Agrawa, & Chaturvedi, 2016). The total cost of using augmented reality is cheaper because the equipment used could vary from high-end gear to a simple smartphone. A smartphone could be used because of the infinite possibilities that applications provide. "Augmented reality applications are cheaper and more efficient ways to enhance human safety" (Agrawal , Acharya , Balasubramanian, Agrawa, & Chaturvedi, 2016). Subchapter 6.6, will elaborate further on the findings regarding the benefits/enablers.

6.3. Construction stages of interest concerning the implementation of AR

The literature shows that AR is presumably beneficial throughout the whole project phase. The life cycle of a construction project consists of a sequence of steps or project phases (figure 23) to be completed in order to reach project goals and objectives. These phases are defined by N. Dawood (2009) as: (2) initiation and outline design, (3) design development, (4) [procurement], contract and pre-construction, (5) construction, and (6) maintenance (Rankohi & Lloyd, 2013).

In addition to the project phases, Augmented reality technology has many applications in the construction industry. In this research the classification of Rankohi and Lloyd (2013) is used to classify AR application areas in the industry (figure 23) as follows: (1) visualization or simulation, (2) communication or collaboration, (3) information modeling, (4) information access or evaluation, (5) progress monitoring, (6) education or training, and (7) safety or inspection.

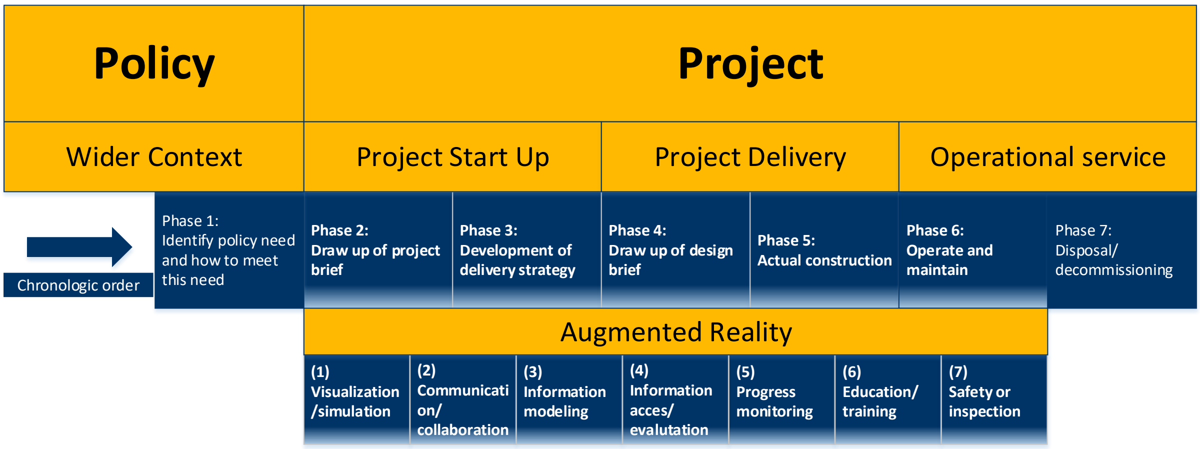

Figure 23, Project delivery phases and classification (Dawood, 2009; Rankohi & Lloyd, 2013) AR

Looking at the interviews, providing a supplement regarding the phases of interest concerning the implementation of AR (chapter 2.5), it stands out that experts confirm the added value for AR in almost all the stages of interest (see figure 23) that were derived from the literature research. Only phase 2, draw up project brief, is found debatable. Some experts believe that AR is of added value in all the 5 phases (Baas, 2019; Smits, 2019). According to other interviewed experts, there is no direct added value for AR in this phase. In their view, VR is cheaper, better, and easier applicable, drawing up the project brief (Zijde, 2019; Hardeveld, 2019; Ginneken, 2019). Hence, the evident stages of interest concerning the implementation of AR are:

- (3) Development of delivery strategy
- (4) Draw up a design brief
- (5) Actual construction
- (6) Operate and maintain

Where the added value is (among other things) in, (3): in the development of delivery strategy, when the basic requirements and or basic design is known, it's possible to take the customer to a location, show the options and ultimately also to place, remove and change them. (4): Use-cases have shown that within engineering concerning standardization, AR is of great added value and leads to a more efficient way of working (Steege, 2019)). So, AR is already proving it's added value in fixed, repetitive processes. In addition, also in construction (5), in which it ensures better communication, visualization detailing, and optimizing other processes within design and engineering (Oldenhave, 2019; Steege, 2019). However, it's debatable whether the current added value within actual construction is high enough. A good example was given by Olden have: "If the only argument is having your hands free, then a screen on the wall will do" (Oldenhave, 2019). So for usage in construction, the case must be better because the current versions (for example workflow visualization) are still too limited. This can, and approximately will improve over time. Think of improving object recognition and enhancing the connection to backend systems. (6): BIM models play a major role in the operations and maintenance phase; therefore, AR can already have an impact. For example, it's always possible to use it for asset management in a completed building.

6.4. Obstructions encountered when implementing AR in construction projects

When implementing AR in construction projects (within the construction industry), some obstructions are encountered. These obstructions were found using literature research, additional document research and interviews with experts. Then, the GTA-method and triangulation were used to process the data. Eventually, 41 obstructions were found, forming seven categories. As can be seen in table 19, below.

Table 19, Condensed list definite obstructions

Condensed list definite obstructions		
Category	**Code**	**Obstructions**
C1: Organizational	**OR1**	Conservative nature of the construction industry
	OR2	Short term result-oriented
	OR3	Not company-wide adopted/implemented
	OR4	Too many decision-makers
	OR5	No sustainable strategy concerning AR
	OR6	Insufficient capacity because of the growing construction market
	OR7	Hard to come by experts/technicians
	OR8	Using 3D and 4D models, not construction industry-wide adopted
	OR9	Problems integrating/matching AR in current processes
C2: Communicational /Collaboration	**CO1**	Poor intern and extern collaboration
	CO2	Afraid of the controlling function ("big brother is watching you")
	CO3	No clear definition of AR
	CO4	Misleading advertisement/impressions causing unrealistic expectations
C3: Informational	**IN1**	Poor quality of (BIM) models
	IN2	Poor information management
	IN3	Fragmentation of knowledge
	IN4	Lack of standardization in information concerning technology tools
	IN5	Lack of commitment to support the information source/model
C4: Financial /Economical	**EC1**	Invisibility of added value
	EC2	Added value currently not high enough for customer/client
	EC3	Large initial investment
	EC4	Wrong cost recovering structure/project cost accounting, no central funding for new technology
	EC5	Uncertainty about Return on Investment (RoI), for example, difficulties quantifying the RoI

C5: Technological	**TE1** **TE2** **TE3** **TE4** **TE5** **TE6**	Hardware limitations Complex software processes, including software and communication issues converting BIM to AR Lack of user-friendly applications Quality of the visuals, for example, occlusion issues and resolution of the visuals Lack of dedicated software The AR field is vast and diverse
C6: Awareness	**AW1** **AW2** **AW3** **AW4** **AW5** **AW6**	Insufficient knowledge on AR (what is AR) Fear for Job replacement No/limited similar (beneficial) use cases Pigeonholing, only looking at it from one's own perspective Lack of acceptance by professionals in the construction industry Unfamiliarity with AR (what are the possibilities with AR)
C7: Operational	**OP1** **OP2** **OP3** **OP4** **OP5** **OP6**	Time-consuming (to make it operational) Additional risk within projects for including AR Not workable in construction environments Change in current processes Physical issues using an AR device (Motion sickness (for example, the HoloLens)) Ruggedness issues, making hardware compliant with safety standards

The obstructions in table 19, were rated on their importance within the construction industry, by different fields of expertise concerning AR technology, using the Fuzzy TOPSIS method. Providing a ranking of the obstructions, whereof the most important obstructions were established using the 80/20 rule. The most important obstructions, including their weight and rank relative to all 41 obstructions, can be seen in table 20 below. Whereof, the three most important obstructions are used to develop a practical recommendation in chapter 7. Using the related and relevant enablers, described in the next subchapter (subchapter 6.5).

Table 20, Most important obstructions in general

Most important obstructions in general (weighting considers all fields of expertise)				
Category	**Code**	**Obstructions**	**Weight**	**Rank**
C1	**OR1**	Conservative nature of the construction industry	0,3646	7
	OR9	Problems integrating/matching AR in current processes	0,3663	5
C3	**IN2**	Poor information management	0,3948	1
	IN5	Lack of commitment to support the information model	0,3776	4
C4	**EC1**	Invisibility of added value	0,3935	2
	EC5	Uncertainty about Return on Investment (RoI)	0,3903	3
C7	**OP6**	Ruggedness issues, making hardware compliant with safety standards	0,3661	6

6.5. Enablers that can help to overcome the most important obstructions

To overcome the most important obstructions and allow for implementation, the enablers concerning AR technology in the construction industry needed to be established. The enablers were also found using literature research, additional document research, and interviews with experts. Then, the GTA-method and triangulation were used to process the data. Eventually, 62 enablers were found, categorized in the same seven categories formed by the obstructions. As can be seen in table 21, below.

Table 21, Condensed list definite enablers

Condensed list definite enablers		
Category	**Code**	**Enablers**
C1: Organizational	**OR-E1**	Organization based funding, not project-based funding
	OR-E2	Standardizing processes
	OR-E3	Incorporating AR into the vision and strategy of the company
	OR-E4	Seeing AR as means to achieve a goal
	OR-E5	Using market/innovation pull
	OR-E6	Adapt service structure, that avoids high initial investments
	OR-E7	Improved process control
	OR-E8	Bad economy allowing for innovation
	OR-E9	Become agile, allowing for fast and easy adaption to change
	OR-E10	Well defined business case, containing a concrete application for AR
	OR-E11	Coordinated way of thing concerning AR
	OR-E12	Distinguishing value for the tender mechanism
	OR-E13	Reducing mistakes and effects
C2: Communicational /Collaboration	**CO-E1**	Knowledge sharing
	CO-E2	Improving stakeholder management
	CO-E3	Improving communication
	CO-E4	Clear definition of AR and what it includes
	CO-E5	Creating trust
	CO-E6	Involve authorized key-decision makers
	CO-E7	Making interaction tangible
	CO-E8	Improve decision-making process
C3: Informational	**IN-E1**	Proper structuring of information in (BIM) models
	IN-E2	Providing insight into the design
	IN-E3	Making information centrally visible
	IN-E4	Traceability of work or service
	IN-E5	Run information flow parallel to the process
	IN-E6	Efficient information management
	IN-E7	Improves 4D scheduling
	IN-E8	Introducing universal protocol
C4: Financial /economical	**EC-E1**	Fewer failure costs
	EC-E2	Advancing feasibility study
	EC-E3	Reducing consultancy costs
	EC-E4	Higher costs-efficiencies

C5: Technological	**TE-E1**	Improving the hardware for automated process monitoring and automated measuring
	TE-E2	Device-independent
	TE-E3	Universal software for converting BIM to AR
	TE-E4	Modular construction of the technology for reusability in different situations
	TE-E5	Compensation of hardware limitation with software
	TE-E6	Defect/error detection
C6: Awareness	**AW-E1**	Including AR in tenders
	AW-E2	Making the added value of the technology visible
	AW-E3	Make the construction industry familiar with the new technology
		Rejuvenation in the construction industry
	AW-E4	An example of an (successful) use-case
	AW-E5	
C7: Operational	**OP-E1**	Improving executability of difficult work
	OP-E2	Supporting optimization of processes
	OP-E3	First-time-right implementation
	OP-E4	Development in small manageable steps
	OP-E5	Digital/testing simulations
	OP-E6	Verification of digital/testing simulations
	OP-E7	Providing work instructions
	OP-E8	Improving quality management
	OP-E9	Enhance scheduling
	OP-E10	Enhance visualization
	OP-E11	Enhance progress tracking
	OP-E12	Faster maintenance interventions
	OP-E13	Remote guidance and supervision
	OP-E14	Supplement shortcoming of on-site BIM use on constructions sites
	OP-E15	Enabling site navigation
	OP-E16	Improve safety
	OP-E17	Cheaper and more efficient way to enhance human safety
	OP-E18	More efficient and effective training/education

Because the three most important obstruction, are also within the two most important categories, they are used as a starting point for answering the main question in the next subchapter (6.6). These obstructions are in order of rank: (1) Poor information management (IN2), Invisibility of added value (EC1), and (3) Uncertainty about Return of Investment (EC5) and can be found in table 20, in the previous section.

In order to choose the best enablers for a practical recommendation, regarding the first steps towards successful implementation of AR in the construction industry, looking at the three most important obstructions, there was close collaboration with the information manager of Heijmans, Sietse Robroch (2019). Together, the relevant enablers were discussed. The below-mentioned enablers of AR, have been found to be the best possible fit as a starting point for giving a practical recommendation on overcoming the three most important obstructions, concerning the implementation of AR in the construction industry.

- **Set up a universal AR protocol**
- **Exemplary use cases**

- **Organization based funding**

These enablers are used to give direction for setting up a practical guide for the first steps toward successful implementation in the next subchapter.

Recommendation

This chapter provides: a course of action towards answering the main research question, a discussion commenting on the methods and limitations of the research, and possible future work arisen from this research.

7. Recommendation

In this chapter, a practical direction towards successful implementation of AR within the construction industry is given. Thereafter, in the discussion the methods and limitations of this research are discussed. Then, the last subchapter provides possible future work arisen from this research.

7.1. First steps towards successful implementation

As described in this report, the implementation of AR is a very comprehensive problem, and so it's not realistic to provide a ready-made solution only based on this research. Therefore, the main research question is answered in the form of a directional and practical guide, describing the first possible steps/points towards successful implementation in table 22, displayed after subchapters 7.3. The guide is intended for contractors within the construction industry. Therefore, this guide was set up in collaboration with the information manager of a contractor within the Dutch construction industry, Sietse Robroch (2019).

7.2. Discussion

For the main analysis, the Grounded Theory Approach was used. However, the theory has a lot of advantages; there are also some disadvantages to using this method. The most important disadvantages are that the subjectivity of the data can lead to difficulties in establishing reliability and validity of approaches and information, and that it's difficult to detect or prevent researchers-induced bias (Glaser & Strauss, 1967; Legewie & Schervier-Legewie, 2004). After the main analysis, the Fuzzy TOPSIS method was used for secondary analysis. As discussed, it's an approach to identify an alternative that is closest to the ideal solution and farthest to the negative ideal solution in a multi-dimensional computing space. The main disadvantage of the method, is the use of Euclidean Distance (the straight line distance between the alternative and the positive or negative ideal solution) does not consider the correlation of attributes. Therefore, it's difficult to weight and keep consistency of judgment (Velasquez & Hester, 2013). However, every effort was made to reduce the impact of these disadvantages; it cannot be excluded that these were of influence.

Continuing with the Fuzzy TOPSIS method, the eventual ranking of the obstructions was based on the total weighted CCj value of all experts combined. Meaning that ranking and weight, on which the final results are based, may not be entirely representative for one of the three fields of expertise secluded.

This research was written with a focus on contractors within the construction industry. As a result of which, it's possible that aspects of this research do not apply to the entire construction industry. When using this research as starting point for other research, this should be kept in mind.

Another important aspect to mention, is that this research was conducted in a time of major developments concerning AR technology. As a result, it is possible additional interesting information for the analyses emerged, after conducting the analyses. This covers a time frame of about three months, because the analyses were conducted somewhere in the third month and the total research time amounted to six months. Also, more interviews could have been collected, providing more data, and more respondents could have been found, giving a more accurate representation of the population. But due to the previously mentioned time frame, this was unfortunately not realistic. It should be noted, that nevertheless, all thresholds for the analyses were met (this refers to the desired number of interviews with experts and respondents for the survey).

7.3. Future work

A lot of data was generated by using the GTA- and Fuzzy TOPSIS method. However, the data was analyzed with a lot of effort, trying to capture all the highlights, some interesting points were left unaddressed. The first point worth mentioning are the enablers. A lot of enablers concerning AR in the construction industry were found and categorized, but eventually only a few were used as a starting point for the practical guide. In future research, these enablers could be further investigated, providing a much broader and deeper understanding of the aspects that enable the use of AR, and which characteristics actually provide the most added value and advantages.

During the interviews, it soon became clear that the knowledge of the AR technology, within the construction industry lies primarily with engineering firms. But because this research was written with an emphasis on contractors, it can lead to new insights looking at the problem from a different (for example, consultant's perspective). To continue, the similarities and differences between the field of expertise were only briefly described and not included in the results. Future research could elaborate on these similarities and differences, and possibly also find more respondents for the interviews, providing a more accurate representation.

Due to the comprehensive size of the research problem, the main research question could not be fully answered. But a practical guide, for contractors, towards answering the main research question was provided, based on the analysis an result. This guide was established in collaboration with the information manager of Heijmans. This means the practical direction was proposed from a limited perspective focused on contractors. Future work can further develop this practical direction by consulting more experts, including more fields of expertise (possibly in combination with the deepening presented in the previous section) and by practically testing the guide. Eventually, creating a widely applicable and usable standard, possibly in the form of an AR protocol, on how to implement AR.

Table 22, Practical guide: first steps towards successful implementation

Practical guide: first steps towards successful implementation		
Steps:	**Enablers:**	**Action:**
Step 1	**Organization based funding** **+** **Advancing feasibility study** **+** **Involve decision-makers**	**Determine how AR is funded within the organization:** AR technology should be financed from a centrally available budget. If there is no central budget for new technologies, one must be created. Hereby, AR becomes more attractive for project managers to include in their projects. With as an ultimate goal, creating change in attitude enabling company-wide support. Advancing the feasibility study on AR provides a clearer picture of the added value of the technology, helping to convince the stakeholders that are responsible, or able, to create the central budget. Also, feasibility studies become more accurate, as more use cases are available to base the study on. Make sure that, from the first moment on, the people authorized for making this decision, are taken into account. This averts delays and stagnation in the implementation process.
Step 2	**Well defined business case** **+** **Creating trust** **+** **Manageable steps**	**Determine if there're similar use cases:** Use cases give insight into the usefulness of the technology in similar projects or similar works and can be used as a reference for other (similar) projects and works. Providing direction for the use of AR within the project and making it easier to determine the possible added value for the new project. *(By including AR within a whole project, and not only partial in the form of a pilot, it will be possible determine the exact pros and cons for that type of project and associated work. By measuring the costs, time and possible reduction of cost and time, advancing the feasibility study described in step 1.)* The construction industry is a relatively conservative industry. Making it difficult to change the current way of working. Prove of positive use cases, in combination with a positive feasibility study, creates trust and confidence for using the technology. Introduction of the AR technology in small manageable steps, gives the employees time to adjust and accept the AR technology, allowing for smoother adoption of the new technology.

Step 3	**Universal AR protocol** **+** **Standardizing processes** **+** **BIM structuring** **+** **Information centrally visible** **+** **Parallel information flow**	**Implementing AR:** After conducting a few successful use cases, it's possible to create a standard template in the form of an AR protocol. This means that the wheel doesn't need to be reinvented every time, resulting in a more efficient AR process. Introducing an AR protocol provides a guide on how to use AR technology according to a certain standard. This enables the right structuring of data (here, as an example, a BIM model is used) using the same "language", providing applicable AR models based on the same standards. By setting a standard for both structuring models and the "language" in an AR protocol, the management of information concerning AR technology becomes a lot less complicated. Standard structuring ensures that the BIM model can be converted device-independent (because the models are always structured in the same way) and then be used by AR devices, without having to adjust them. The uniform "language" prevents miscommunication. Including communication and data flows in the protocol, on how the communication should take place, where the data should be stored and how the data should be stored, makes it easier to control the information flows with regard to the technology. Note these communication and data flows should be set before starting a project and maintained by information management of the responsible parties in order to prevent deviation from set agreements and thereby caused errors. By setting up a central database for storing the data, the information concerning AR will be centrally visible, facilitating broad employability of AR and easy access to the information. Lastly, the information flows should run parallel to the process. This allows for including changes in information and adding information proportional to the building cycle in an information model (for example, a digital twin).
Step 4	**Clear definition on AR** **+** **Include AR in tender** **+** **Rejuvenation**	**Improving the familiarity on AR:** Provide a clear definition of AR and what the AR technology includes for the organization. Setting realistic expectations for the clients and industry. This prevents AR from becoming a gimmick and creates trust with customers. (*Often organizations advertise with AR cases and applications, that they can't actually deliver. They use AR almost purely for marketing and or conviction (for*

		example: more budget) and for that purpose, overpromise. Creating wrong or unrealistic expectations (for AR), fed by the lack of clarity regarding the definition of AR.) If clients are confident that the technology offers added value for their project and can trust that this added value can be realized, it is possible that the technology will ultimately be included in the terms for tenders. Convincing the client is currently the task of the contractor, they have to point out the possibilities and advantages that can be achieved by using the technology, because clients in the construction industry have an inactive attitude with regard to new technologies. They do not know that technology exists or do not immediately see the benefits of it and therefore do not use it. (*When the technology has proved itself, the clients will automatically start including it in relevant tenders. By relevant tenders is meant, tenders where for the AR technology can be beneficial. Which in turn, will be a boost for those parties that do not yet include AR.*) The last point of step 4 is, take care of rejuvenation by employing new graduates that are familiar with progressive technologies (among which AR). It is often seen that universities are at the forefront when it comes to knowledge about new technologies. Hiring graduates has the advantage that they are not stuck in a certain way of working (conservative nature of employees with experience in the construction industry), and are already familiar with the technology. This allows them to advance technology within the company and take the “old guard” with them in the process. By “old guard” is meant: employees who have been working in the construction industry for quite some time, often with a lot of experience and persistent to old customs (conservative nature). (*Eventually, the contractors themselves must be convinced of the fact that AR can improve their processes, instead of being just a USP for a project. Because this way AR is only pulled off the shelf to win projects, which ignores the way in which the technology can really offer added value, and that is the incorporation of the technology within the business processes*)

Step 5	**Modular construction** **+** **Universal software platform** **+** **Device-independent** **+** **Improving the hardware**	**Making the AR technology better workable:** By designing the AR technology, based on a modular construction/building blocks, it becomes reusable and scalable. Making the same technology usable for different applications. This means that it is not necessary to start more or less over each time the application changes. The universal AR protocol allows for a universal software platform for easy converting from BIM to AR file, ready to upload into an AR (ready) device. (*Software platforms for converting already exist, but no universal platforms. The current lack of standardization causes the need for different converting platforms and applications. These are needed to address the different software (standards) used for information models and by AR (ready) devices.*) As already mentioned in step 3, standardization also allows for device-independent use of AR. Independently means that the technology is broader applicable and easier to use in different situations, and therefore allows for easier adoption. It also makes it easier to give people a hands on experience and get familiar with the technology (familiarity is discussed in step 6). The hardware needs to be improved, with as a main focus the operational usability. Some important aspects are the need for larger processing capacity, better field of view regarding AR glasses, better ergonomics, a higher level of detail, a higher level of precision with a maximum deviation of 1 mm, good connectivity, and better readability from screen or lenses in all circumstances. These improvements will make AR broader applicable and easier adoptable.
Step 6	**Stimulate familiarity** **+** **Knowledge sharing**	**Advancing the AR technology:** Everyone in the company should be familiar with AR. They don't need to know all the preconditions, but they must be familiar with the concept and know what is going on. This is done by including AR in the overall vision, ideas, and having a strategy concerning the technology. Furthermore, giving presentations, doing lectures, and organizing pop-up events, can be valuable additions in the process of making AR familiar. AR technology should be brought to the employees (preferably experienced by a

		hands-on experience). This gives them the chance to get a feel for the technology and learn about the added value, which stimulates the acceptance and will to use the technology. In the ideal situation, the whole construction industry should be familiar with the technology. Knowledge sharing throughout the whole industry facilitates this process, allowing for even faster adoption and development regarding AR.

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Appendices

Appendices	
Chapter:	**Title:**
Appendix I	Interview questions for experts on AR in the Dutch construction sector
Appendix II	Categorization table (definite Obstructions and Enablers)
Appendix III	Closeness coefficient per obstruction per field of expertise

Appendix I

Interview questions for experts on AR in the Dutch construction sector
➢ **Naam:** ➢ **Functie:** ➢ **Bedrijf:** ➢ **Datum:**
Vragen:
De bouw is een conservatieve sector, is er in uw optiek drang naar verandering? ➔ Antwoord: ja → Waar baseert u dit op? En wat voor soort verandering? ➔ Antwoord: nee → Hoe komt dit?
Hoe zou u AR definiëren?
Hoe bent u momenteel bezig om AR van de grond te krijgen? ➔ Wat zijn de grootste uitdagingen?
Aangaande de algehele bedrijfsvoering: • Wat is de centrale visie/strategie aangaande AR? • Wat zijn de algemene doelstellingen aangaande AR?
Hoe verloopt de implementatie van AR binnen de Nederlandse bouwsector? ➔ En hoe wordt dit verloop verklaart?
Wat is momenteel het aandeel (impact, in hoeverre wordt AR meegenomen in het projectproces) van AR in de projecten waarmee u zich bezig houdt? Aangaande projecten: • Hoe wordt AR meegenomen in de scope en vervolgens vertaald naar eisen? • Hoe wordt er voor gezorgd dat AR niet wordt wegbezuinigd in economisch slechtere tijden?
Hoe beïnvloedt AR het besluitvormingsproces?
Hoe kan AR het beste meegenomen worden in het bedrijfsproces (geïmplementeerd worden)? ➔ Op strategisch niveau ➔ Op tactisch niveau - Wijze van implementatie - Randvoorwaarden implementatie - Standaarden
Hoe kan het bouw (monitoring)proces optimaal worden ingericht voor het gebruik van AR? ➔ Operationeel niveau
In welke fase of fases van constructie is AR volgens u het best toepasbaar? ➔ Conform de volgende fasering: 1. Marktvraag/initiatie en schetsontwerp 2. Ontwikkeling van het ontwerp 3. Contract en pre-constructie (aanbesteding) 4. Constructie 5. Onderhoud
Welke aspecten van het bouwproces hebben volgens u het meeste baat bij AR?
Hoe kan AR in de toekomst het constructieproces in de Nederlandse bouwsector verbeteren?
Slotvragen:
Wat zijn de problemen met betrekking tot veiligheid en privacy aangaande AR?
Wat is u persoonlijke (toekomst) visie omtrent AR?

Appendix II

Categorization table (definite Obstructions and Enablers)							
	Selective coding						
	Organizational	Communicational/ collaboration	Informational	Financial/economical	Technological	Awareness	Operational
Obstructions Interviews	(1) Conservative nature (2) Short term result oriented (3) Not company-wide adopted/implemented (4) Too many decision makers (5) No sustainable strategy concerning AR (6) Booming construction market	(7) Poor intern and extern collaboration (8) Afraid of controlling function (9) No clear definition of AR (10)Misleading advertisement/impressions	(11)Quality BIM-model (12)Poor information management (13)Fragmentation of knowledge	(14)Invisibility of added value (15)Added value currently not high enough for customer/client (16)Large initial investment (17)Cost recovering structure / project cost accounting	(18)Hardware limitations (19)Complex software processes	(20)Insufficient knowledge on AR (21)Fear for job replacement (22)No/limited similar (beneficial) use cases (23)Pigeonholing	(24)Time consuming (25)Additional risk within projects (26)Not workable in construction environments (27)Change in current processes
Obstructions Document Research	(28)Hard to come by AR experts/technicians (29)Using 3D and 4D models not construction sector wide adopted (30)Occlusion with current processes		(31)Lack of standardization in information concerning technology tools (32)Lack of commitment for support of information source/model	(33)Uncertainty about RoI	(34)Lack of user friendly applications (35)Quality of the visuals (36)Lack of dedicated software (37)AR field is vast and diverse	(38)Lack of acceptance by professionals in the constructions sector (39)Unfamiliarity with AR	(40)Motion sickness (41)Safety issues (Making AR hardware compliant with safety standards such as processing 'ruggedness').
Enablers Interviews	(1) Organization based funding (not projects) (2) Standardizing processes (3) Incorporating AR into the vision and strategy of the company (4) Seeing AR as means (to achieve a goal) (5) Market/innovation pull (6) Service structure (7) Improved process control (8) Become agile, allowing for fast and easy adaption to change (9) well defined business case, containing a concrete application for AR. (10)Coordinate way of thinking concerning AR (11)Tender mechanism (distinguishing value)	(12)Knowledge sharing (13)Improving stakeholder management (14)Improving communication (15)Clear definition of AR (and what AR includes) (16)Creating trust (17)Involve the decision makers	(18)(BIM) Model Information structuring (19)Providing insight in the design (20)Information centrally visible (21)Traceability of work or service (22)Run information flow parallel to the process (23)Introduce universal AR protocol (24)Introduce universal AR protocol veranderen in supplement	(25)Less failure costs (26)Advancing feasibility study (27)Reducing consultancy costs	(28)Improving the hardware for automating process monitoring and automated measuring (29)Device independent (30)Universal software platform for converting BIM to AR (31)Modular construction of technology (reusable in different situations) (32)Compensation of hardware limitations with software	(33)Including AR in tenders (34)Making added value visible (35)Familiarity with AR (36)Rejuvenation in the construction sector (37)Example (successful) use case	(38)Improving executability of difficult work (39)Supporting optimization of processes (40)Correct method of implementation (41)Develop in small manageable steps (42)Verification of simulation (43)Digital testing/simulation (44)Providing work instructions

Enablers Document Research	(45)Reduce mistakes and defects	(46)Making interaction tangible (47)Improve decision making process	(48)Efficient information management (49)Improved 4D scheduling	(50)Higher cost-efficiencies	(51)Defect/error detection		(52)Better quality management (53)Enhance scheduling (54)Enhance visualization (55)Enhance progress tracking (56)Faster maintenance interventions (57)Remote guidance and supervision (58)Supplement shortcomings BIM on-site use in construction (59)Enabling site navigation (60)Improve safety (61)Cheaper and more efficient ways to enhance human safety (62)More effective and efficient training/education

Appendix II

Weighting per obstruction: Consulatncy			
Obstructions	D+(sum)	D-(sum)	CCj
OR1	3.6501	6.7769	0.649941
OR2	4.6512	5.4681	0.540361
OR3	4.1143	5.8374	0.58657
OR4	4.3999	5.3808	0.550144
OR5	4.1654	5.6353	0.574985
OR6	4.5724	5.1020	0.527375
OR7	5.2863	4.4762	0.458511
OR8	4.9247	5.2227	0.514683
OR9	4.2575	5.4787	0.562716
CO1	5.6805	4.4769	0.440753
CO2	6.6244	2.6465	0.285465
CO3	5.3287	4.4142	0.453069
CO4	5.2274	4.3987	0.456958
IN1	5.1178	5.0118	0.494764
IN2	4.2009	6.0746	0.591176
IN3	4.8040	5.3808	0.528317
IN4	5.6904	4.7657	0.455779
IN5	4.8411	5.7706	0.543797
FI1	3.0894	7.1469	0.698193
FI2	4.2220	5.8950	0.582682
FI3	4.2178	5.9768	0.586273
FI4	4.2398	5.4611	0.562951
FI5	3.0226	6.8404	0.693542
TE1	4.3098	5.8202	0.574553
TE2	5.3110	4.8008	0.474774
TE3	4.2575	5.8829	0.580146
TE4	5.3716	4.2829	0.443619
TE5	5.3267	4.3526	0.44968
TE6	5.2933	4.3790	0.45274
AW1	4.5519	5.5142	0.5478
AW2	6.4763	3.1920	0.330152
AW3	3.8880	5.8027	0.598788
AW4	4.4780	5.1787	0.536279
AW5	4.9036	5.4291	0.525427
AW6	4.7973	5.4970	0.533985
OP1	4.8547	5.2678	0.520404
OP2	6.3191	3.3263	0.344857
OP3	5.8525	3.7826	0.392586
OP4	5.9675	4.2260	0.414575
OP5	5.2524	4.5267	0.462897
OP6	4.6261	5.0393	0.521376

Weighting per obstruction: Consulatncy			
Obstructions	D+(sum)	D-(sum)	CCj
OR1	3.6501	6.7769	0.649941
OR2	4.6512	5.4681	0.540361
OR3	4.1143	5.8374	0.58657
OR4	4.3999	5.3808	0.550144
OR5	4.1654	5.6353	0.574985
OR6	4.5724	5.1020	0.527375
OR7	5.2863	4.4762	0.458511
OR8	4.9247	5.2227	0.514683
OR9	4.2575	5.4787	0.562716
CO1	5.6805	4.4769	0.440753
CO2	6.6244	2.6465	0.285465
CO3	5.3287	4.4142	0.453069
CO4	5.2274	4.3987	0.456958
IN1	5.1178	5.0118	0.494764
IN2	4.2009	6.0746	0.591176
IN3	4.8040	5.3808	0.528317
IN4	5.6904	4.7657	0.455779
IN5	4.8411	5.7706	0.543797
FI1	3.0894	7.1469	0.698193
FI2	4.2220	5.8950	0.582682
FI3	4.2178	5.9768	0.586273
FI4	4.2398	5.4611	0.562951
FI5	3.0226	6.8404	0.693542
TE1	4.3098	5.8202	0.574553
TE2	5.3110	4.8008	0.474774
TE3	4.2575	5.8829	0.580146
TE4	5.3716	4.2829	0.443619
TE5	5.3267	4.3526	0.44968
TE6	5.2933	4.3790	0.45274
AW1	4.5519	5.5142	0.5478
AW2	6.4763	3.1920	0.330152
AW3	3.8880	5.8027	0.598788
AW4	4.4780	5.1787	0.536279
AW5	4.9036	5.4291	0.525427
AW6	4.7973	5.4970	0.533985
OP1	4.8547	5.2678	0.520404
OP2	6.3191	3.3263	0.344857
OP3	5.8525	3.7826	0.392586
OP4	5.9675	4.2260	0.414575
OP5	5.2524	4.5267	0.462897
OP6	4.6261	5.0393	0.521376

Weighting per obstruction: Contractors			
Obstructions	D+(sum)	D-(sum)	CCj
OR1	2.7571	3.0523	0.5254
OR2	2.3708	3.4741	0.5944
OR3	2.8980	2.9041	0.5005
OR4	2.5640	3.2632	0.5600
OR5	3.0463	2.7628	0.4756
OR6	2.8532	2.9737	0.5103
OR7	3.4680	2.3762	0.4066
OR8	3.1266	2.7283	0.4660
OR9	1.5973	4.2023	0.7246
CO1	2.4491	3.3780	0.5797
CO2	3.4680	2.3762	0.4066
CO3	3.7918	2.0065	0.3460
CO4	2.5640	3.2632	0.5600
IN1	2.5294	3.3435	0.5693
IN2	1.5627	4.2826	0.7327
IN3	2.3008	3.5192	0.6047
IN4	2.3008	3.5192	0.6047
IN5	1.5973	4.2023	0.7246
FI1	1.4387	4.3329	0.7507
FI2	2.5640	3.2632	0.5600
FI3	3.3197	2.5174	0.4313
FI4	2.7226	3.1325	0.5350
FI5	2.3185	3.5368	0.6040
TE1	1.8082	4.0090	0.6892
TE2	2.7571	3.0523	0.5254
TE3	3.3720	2.4547	0.4213
TE4	1.8082	4.0090	0.6892
TE5	2.9680	2.8589	0.4906
TE6	3.4504	2.3586	0.4060
AW1	2.9157	2.9216	0.5005
AW2	4.1958	1.6022	0.2763
AW3	2.0013	3.7981	0.6549
AW4	2.7049	3.1150	0.5352
AW5	2.6423	3.1671	0.5452
AW6	2.5117	3.3259	0.5697
OP1	2.7226	3.1325	0.5350
OP2	3.1089	2.7107	0.4658
OP3	1.4042	4.4132	0.7586
OP4	2.5294	3.3435	0.5693
OP5	2.0013	3.7981	0.6549
OP6	1.4387	4.3329	0.7507

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