Construction Robotics Technologies

2030

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Foreword

I chose construction robotics as my graduation lab because of my personal experience in childhood. Since the middle 20th century, China, after lagging behind the western world for several centuries, has taken 'modernization' of the country as its primary goal. The image of humanoid robots, as a representative of the concept modernization, appeared a lot in preschool educational publications, impressing me greatly, and become a part of my memory. Therefore, I chose the construction robotics lab to do some work related to robots in my graduation project.

Now, with more and more technologies appearing, the whole picture of the technical innovations in construction robotics is becoming complicated, sometimes even confusing. The purpose of this research is to figure out what technologies are employed to assist robotics in the Dutch construction practice and explore the possible futures of these technical innovations in construction robotics in 2030. By considering the possible social, economic and technological changes, a set of scenarios are established, to infer the possible evolvement of the currently used and emerging technologies in the next decade. The scenarios are then used to identify the technologies which benefit the construction industry across the possible futures. This report provides an overview of the study.

Summary

Background and research question

The construction industry is a major economic sector in most countries, taking a considerable part of the economy (Chartered Institution of Building, 2016). However, until the middle age of the last century, the construction industry still worked in a traditional way, leading to a relatively low productivity when compared with other industrial sectors. As an effort to solve the problem, robots and robotics have been introduced to improve the efficiency and productivity in this industry. The research of construction robotics has increased a lot since the 1980s.

In the recent two decades, two distinct trends could be observed in studies of construction robotics. First, the construction robotics is expanding its interests to more tasks. At the beginning phase, construction robotics mainly aims at the replacing human labors in some simple and repetitive works to enhance efficiency and improve quality, for instance, polishing the floor and painting the wall, laying the bricks. These works directly produce physical environments, delivered as the first type of tasks in this study. In the recent decade, however, construction robotics has begun to involve in some new tasks, which are not directly related to the building of 'real entities', but aiming at improving the process of the construction activities, e.g., the construction safety management, quality control, site planning, etc.

The second trend is the fact that more and more technologies are involved in construction robotics. In the 1980s, the papers of ISARC (International Symposium on Automation and Robotics of Construction) mainly discussed those mechanical and engineering technologies that could be used to build automatic robots for specific single tasks in construction. In the recent years, however, influenced by the trend of informatization of the construction industry, more technologies are involved, for example, BIM, Internet of Things, Wireless Sensing, and Laser Scanning.

These new trends make the landscape of the technical innovations in construction more complicated. However, so far, there is neither an overview of the technologies used in construction nor an analysis of the possible futures of the technical innovation. Thus, it is not easy for the practitioners to get a whole picture quickly, which has lowered their willingness to adopt new technologies in practice; also, the diverse technologies may cause difficulties in deciding where to invest the limited resources for Research & Development (R&D).

Therefore, this research aims to summarize the currently available technologies in the construction robotics and to depict the possible future landscapes. The main research question is,

In the Dutch construction industry, what technologies are available to enhance the robotics level and what are the possible futures of technical innovations in construction robotics in 2030?

The main research question is decomposed to three sub-questions.

Sub Question 1: What are the states of the art of construction robotics?

The answer to this question is the base of the research. In this part, the tasks that construction robotics concerns and the available technologies are identified. The outcomes of this sub-question provide inputs for the future research to answer the latter two sub-questions.

Sub Question 2: Currently, what technologies are available to enhance the robotics level in the Dutch construction industry?

This sub question explores the currently applied and emerging technologies in construction robotics. The outcomes will be used as input for the future study in the next step.

Sub Question 3: What are the possible landscapes of construction-robotic technologies in the Netherlands in 2030?

The future landscape consists of two parts: the future development of the currently available technologies, and the new technologies that may spring up in the future. It is impossible to foresee new technologies that do not exist now, even for the experts; and there is not a solid method to do so. Therefore, it does not make much sense to focus on the currently nonexistent technologies, which were finally skipped. Thus, the future exploration is not complete, but focusing on the more significative part, mainly analyzing the possible evolvement of the current technologies.

Because of the limited time, it is not possible to examine through the whole construction industry. Therefore, two tasks are selected to be studied in detail. They are construction-assembly works and construction safety management.

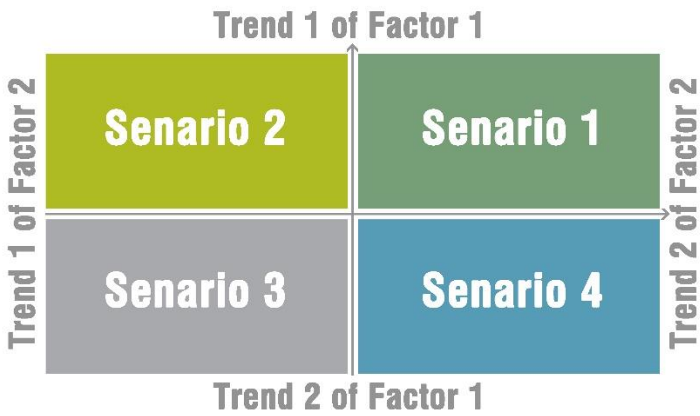
Methodology

The first sub-question is answered by systematic literature review. The ISARC proceedings are used as a valuable resource, to identify the construction tasks concerned by construction robotics, as well as the categories of the technologies currently available, as inputs for the further research.

The second sub-question is answered by a detailed literature study, focusing on the publication in the two selected fields, to figure out the currently available technologies. Then expert interviews are conducted to combine the literature study with the Dutch practice, to see how these identified technologies' have been applied in the Netherlands. The final product of this sub-questions is an overview of the currently available techniques assisting the two tasks, including their working principles, added values, application in the Dutch construction industry, and the drivers and barriers of their implementation.

This research answers the third sub-question using a scenario-planning-based method. The future is difficult to forecast, affecting by many uncertainties. To manage these uncertainties, a set of scenarios are established, based on the most relevant uncertain factors. The most relevant factors refer to those with high impacts on the future development of construction-robotic technologies, and at the same time, are highly uncertain, without a predictable trend in the next decade. The matrix in Figure S.1 indicates how the scenarios are built. Experts are interviewed to identify the relevant factors and evaluate their impacts and predictabilities. Finally, two factors with high impacts and low predictabilities are selected to construct a scenario matrix.

Figure S.1 The scenario matrix



By analyzing the evolvement of the current technologies in the planned scenarios, a set of the future landscapes could be depicted. The technologies located in the overlap of the different scenarios can bring benefits across all the possible futures, and therefore, are the most solid zone to invest in for both practitioners and researchers.

The states of the art of construction robotics

By systematically reviewing the ISARC papers since 2012, sixteen construction tasks concerned by construction robotics are identified, as shown in Table S.1. They can be classified into two types of works: the first type refers to the tasks that produce built environments, e.g. earthwork, masonry, floor polishing, etc. The works belonging to the second do not directly generate the physical entities but help to improve the construction process, e.g. safety management, site planning, and quality control.

Among the identified tasks, two are selected to be studied: **Construction Assembly** and **Construction Safety Management**. The process of selection is elaborated in Appendix B.

Table S.1 The tasks concerned by construction robotics

Identified tasks in the on-site construction work	
Cluster	Tasks
First type: directly related to the physical production	Earthwork
	Reinforcement
	Paving
	Concrete distribution
	Concrete finishing
	Welding
	Coating
	Assembly
	Interior finishing
	Masonry
	Surveying and monitoring

Second type: related to the construction process	Logistics
	Site planning and management
	Safety
	Quality control
	Process management

Eleven categories of the technologies employed in construction robotics are identified, as shown in Table S.2. The application of these technologies is briefly described in Appendix A.

Table S.2 Identified technologies

Technologies involved construction robotics	**Abbreviation**
Internet of Things	IoT
Additive Manufacturing	AM
Modularization & Prefabrication	M&P
Automation and Robot	A&R
Human-Computer/Robot- Interaction	HCI/HRI
Laser Scanning and Photogrammetry	L&P
Virtual Reality/ Augmented Reality	VR/AR
Building Information Modelling	BIM
Simulation and Algorithm	S&A
Cloud Computing	CC
Big Data	BD

Most of the construction robotics studies focus on the second type of work. In the first type of works, construction robotics concerns earthwork and assembly work most, while in the second type site management, safety management, and process management. The most employed technologies in construction robotics are Automation and Robot, BIM, Software and Algorithm, CPS/IoT. The latter three are related to the informatization and intelligentialization in construction.

Currently available technologies (in the selected two tasks)

Currently, the robotics level of the construction-assembly works in the Dutch construction industry is quite low. Although some of the technologies identified by literature study have applied in pilot projects in the Netherlands, none of them is implemented on a large scale. Some of these technologies are both technically and financially feasible, and the most major barrier for their application is the conservativeness of practitioners and the lack of imagination. Among the clusters of technologies identified in Chapter 3, six have been applied in construction-assembly works, or at the prototyping phase. These clusters include IoT, Automation and Robot (Handling Robots, Single-Task Robots/Robotic System, Construction Factory, Bottom-up System), Laser Scanning and Photogrammetry, BIM, and Cloud Computing (Figure 6.1).

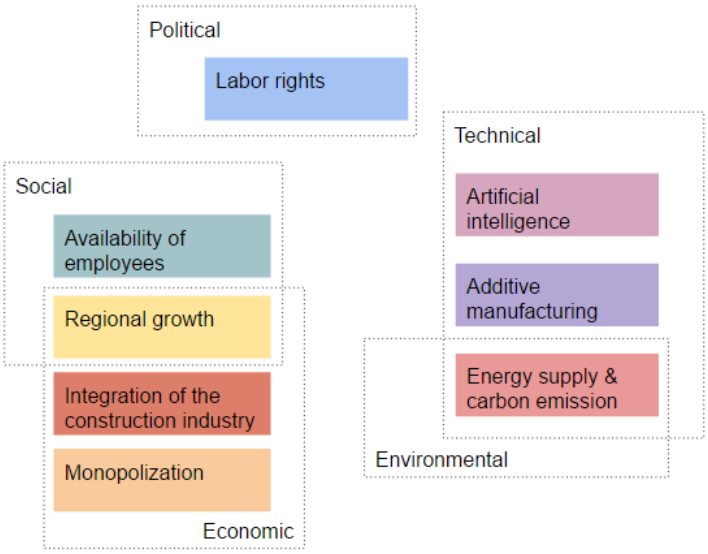
As a 'second type work', safety management is a relatively new field of construction robotics. Unlike the first type works, safety management does not involve many heavy and repetitive manual works. Its essence is the management of hazards information, including collecting information, processing information and sending the information efficiently to the related on-site workers to avoid the hazards. Therefore, the mostly applied technologies in this field are those related to information management. Meanwhile, those 'traditional' mechanical technologies are very scarcely applied. Five of the eleven identified clusters of technologies in Chapter 3 are employed in the construction safety management, including Internet of Things (Wireless Sensing, Wearable devices), Virtual Reality and Augmented Reality, BIM, Simulation and Algorithm (Virtual Prototyping), and Big Data (Figure 6.2).

Details of the currently available technologies in these two tasks could be found in Table E.1 and E.2(Appendix E).

Future landscapes of the technical innovations in construction robotics (in the selected two tasks)

The first step in the future study is to build scenarios for the future development of the construction robotic technologies. By talking with experts, eight factors are abstracted, as shown in Figure S.2.

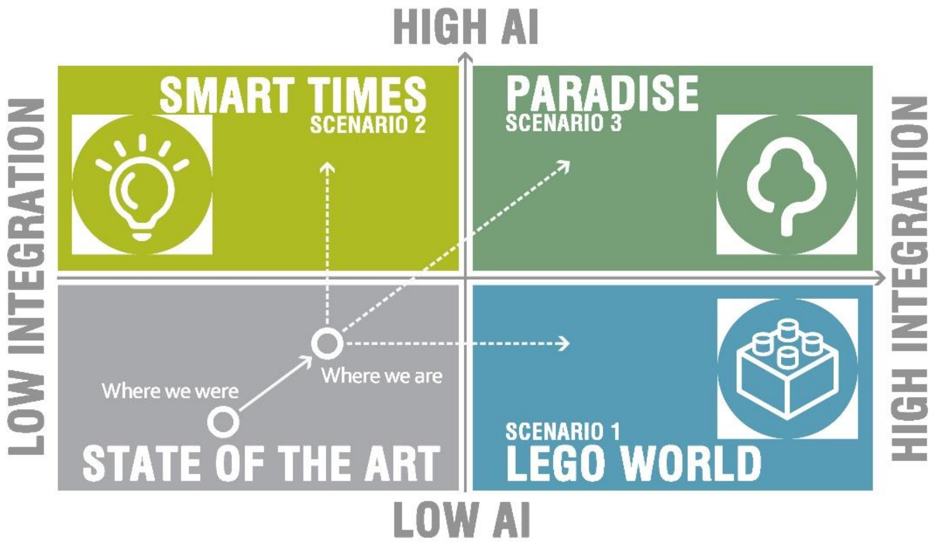
Figure S.2. Identified factors that may affect the future development of construction-robotic technologies



Then the participating specialists are required to evaluate their impacts and uncertainties via an online questionnaire (Appendix D). The result of the assessment indicates are illustrated in Figure S.4. Finally, the two factors ***Artificial Intelligence*** and ***Integration of the Construction Industry*** are selected to establish the scenarios.

A matrix is established, with the four quadrants, representing current situation, and three possible scenarios of the future respectively (Figure S.3).

Figure S.3. The scenario matrix



The scenarios and the future landscapes of technical innovations in these scenarios are described as follows.

Scenario 1: LEGO WORLD

In this scenario, the integration level of the construction industry is developed greatly. Meanwhile, the other factor which is used to construct the scenarios, Artificial Intelligence, has not got significant development. In this scenario, more big companies dominate the construction market, integrating all the phases in the building activities, from design, building, to operation and maintenance. As a result, the small, daily life buildings (e.g. residential houses) have been brandised, similar to the situation in the car and cell phone industries. Standard products take a large share of the market, which are designed by the suppliers, and partly built in the globally-distributed producing system. Then the modular and components are sent to clients' site to be erected. This trend also affects the large and complex buildings. Although they cannot be completely standard, the major suppliers on the construction market try their best to construct these buildings using the standard modular they produce, for instance, the staircases, bathrooms, and toilets. Human workers still play an important role in the construction activities, as AIs are still not powerful enough to take over the most of the works.

BIM stands in the central place in construction-assembly works. It provides spatial and sequential information of the projects, supporting assembly processes. For instance, it gives the information about the final location of a specific component so that its most convenient conveying path could be calculated; BIM also provides the assembly sequence, helping the managers to order the materials needed for the projects. With the on-site Internet of Things (IoT), the information and video guides could be distributed to the related workers, being displayed to them intuitively on the screen of AR devices. Thus, the efficiency of construction assembly is enhanced. Robots are employed in the whole process to assist human labors. Compared with twenty years ago, they are much smaller and lighter, therefore easier to be used. Human-Robot-Interaction technologies are used to improve the cooperation between human beings and robots. High modularization level brings many large components, and large handling robotics are employed to handle them, such as gantry cranes. As the large companies dominate the market, Construction Factories are implemented more than before. The Bottom-up systems are implemented to some extent. In some inspection works (for instance the assembly of MEP devices), laser scanning and photogrammetry are employed to quickly construct a digital model of the built environment and compare it to the BIM model, to assist the inspecting process. The data of the whole assembly process in a project is collected by the

IoT on site. The Big Data analysis provides some information for project management and decision making. For example, when a manager is trying to plan a path for a component to be conveyed by simulation, the paths of other materials, equipment and workers are necessary for the simulation to avoid collision and congestion; Big data helps to analysis the related information. Analysis of the inspection data helps to figure out the works in which flaws may happen; Cloud computing is employed in the process, helping each part of the project can access the updated information through the cloud databases.

In the field of safety management, similarly, BIM and IoT also play the most significant roles, because they are responsible for information provision and distribution. Using the information of the construction activities provided by BIM, specific software helps to simulate the building process and identify the possible dangers. Virtual Reality (VR) helps the safety managers to observe the construction site to find more hazards. Then AR devices connected to the IoT display the potential hazards visually to the workers to enhance their awareness. The IoT at the same time monitor the real-time location of all the objects on site and their proximity, to avoid collisions. Big Data is employed to analyze the motion of on-site workers to detect the near-miss accidents and correct their gestures to avert Muscle-Skeleton Disorders (MSDs). It also could be used to analyze the hazards data, to figure out the pattern of dangers, feeding back the results to the cloud database, to assist safety planning in future projects.

Scenario 2: SMART TIMES

In Scenario 2, Artificial Intelligences have developed so significantly that they are able to take over the management of construction activities, and human workers play the role of supervisors. Almost everything is automatic, making it a 'Smart times'. Information technologies, therefore, play a crucial role in this scenario. Robots are employed to execute the onsite works which were done by human labors in the past. Thanks to the assistance of AIs and robots, construction companies can go with fewer employees than before.Therefore, many small companies survive and are active on the market. On the other dimension of the scenario-planning matrix, the integration level is relatively low. The construction industry keeps on the original path, highly depending on the on-site works.

In construction-assembly works, similar to Scenario 1, the combination of BIM and IoT takes the central position, providing information, supporting simulation, monitoring the assembly, and collecting data from the process. Robots are widely employed in construction activities to replace human workers. However, different with Scenario 1, the handling robots and single-task robots are replaced by swarm robots, which are standardized and multi-functional, more flexible to organize in projects, and cheaper and easier to maintain. Augmented Reality (AR) and Human-Robot-Interaction (HRI) technologies, which are related to the human workers on site, will continue to be used, but on a very limited scale, because there are scarce on-site workers that require human workers to deal with. Construction Factories' implementation remains the situation of twenty years ago, but the Bottom-up system becomes more popular than before. Big data is also employed to support the conveying path analysis and to figure out the pattern of possible flaws' distribution in inspection phase.

In construction safety management, BIM, IoT, Cloud Computing and Simulation contribute most to the enhancement of the performance. As the on-site human workers have almost disappeared, the application of those technologies that related to the safety of human workers' safety are also limited to a small scale. For instance, AR, VR, and the gesture monitoring systems. Big Data used to be employed to monitor the motion of on-site workers; now it is mainly used for the hazards' data analysis.

Scenario 3: PARADISE

In Scenario 3, the construction industry gets progress in both of the two dimensions. Controlled by AI, the construction activities are highly automatic, without too much human intervention. Some construction companies evolve into versatile enterprises, containing in-house capability of designing, building, operating and maintaining, providing standard products, or semi-standard products, which mainly consists of the standard modular they produce. At the same time, AIs' application helps many small companies to survive. Thus, the monopolization level of the market is medium.

Assembly works in construction mainly relies on BIM and IoT; Simulation, Big Data, Laser Scanning and Photogrammetry also contribute; Cloud Computing helps the different terminals on site (equipment and robots) to share related information in real time. In this scenario. Similar to Scenario 2, the human-worker-related technologies, including HRI and AR, are scarcely used. Both of the on-site Construction Factories and Bottom-up Systems get more used than before.

The technologies applied in safety management in this scenario share the same future landscape with Scenario 2.

The overlap of the different scenarios: solid field to invest

The overlap of the three scenarios is the most solid fields for related actors to invest in the next decade. The budgets spent in these areas, purchasing devices, including training workers, researching and developing related technologies, enjoy a lower risk of going to waste.

In construction-assembly works, these fields include **BIM**, **Internet of Things**, **Robots, Cloud Computing**, and **Bottom-up system**. In the area of construction safety management, **BIM**, **Simulation**, **Internet of Things, Cloud Computing,** and **Big Data** will probably be the 'safe zones' for the contractors to invest in the future decade.

Content

1. Introduction

Key point

- Construction is a crucial economic sector in almost every nation, including the Netherlands, taking a considerable share of the economy and employment. However, the productivity of the construction industry lags behind other sectors.
- Robots and robotics have been employed in the construction industry to enhance efficiency and productivity, and the research in construction robotics field has boomed since the 1980s. In recent years, two trends could be observed in the evolvement of construction robotics. First, construction robotics is employed in more tasks; second, more and more new technologies have been involved.
- The two trends make the landscape of construction robotics more complicated. However, no overview about of the dazzling construction robotic technologies is available yet, nor an analysis of the possible future development of the technical innovations in construction.
- Trying to fill the gap, this research summarizes the existing and emerging technologies and depicts the possible future landscapes in construction robotics. Thus, the main research question is, **In the Dutch construction industry, what technologies are available to enhance the robotics level and what are the possible futures of technical innovations in construction robotics in 2030?**

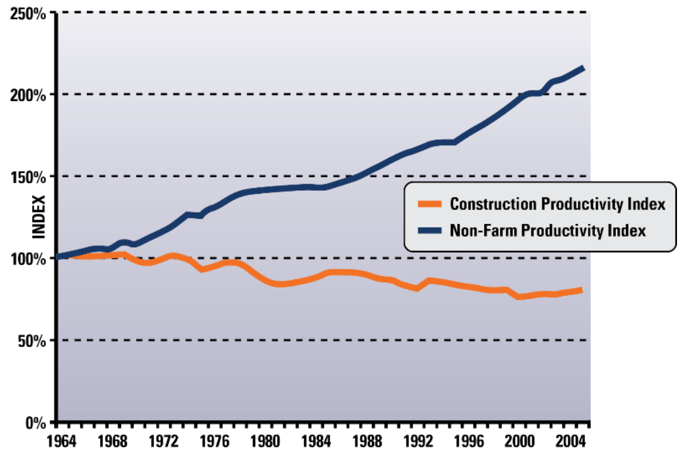
1.1 Research questions and deliverables

Construction as a major economic sector

Construction is one of the oldest industries, as well as one of the most important economic sectors, contributing 9-15% GDP in most countries (Oesterreich & Teuteberg, 2016). Construction is widely related to almost every aspect of the society, including housing, infrastructure, transport, other industries, businesses, and services. In 2014, the European countries invested 1.37 trillion euros in construction (Oesterreich & Teuteberg, 2016). In the Netherlands, the construction industry also plays a significant role. In the year 2013, this sector provided 524,800 jobs, with a total operating return of 78,233 million euros (CBS, 2016).

However, compared with other economic sectors, the construction industry suffers from relatively low efficiency. Figure 1.1 illustrates the change of productivity in different economic sectors in the US. Between 1964 and 2004, the productivity of all the non-farm industries increased by over 100%, meanwhile in the construction industry, the productivity decreased by almost a quarter.

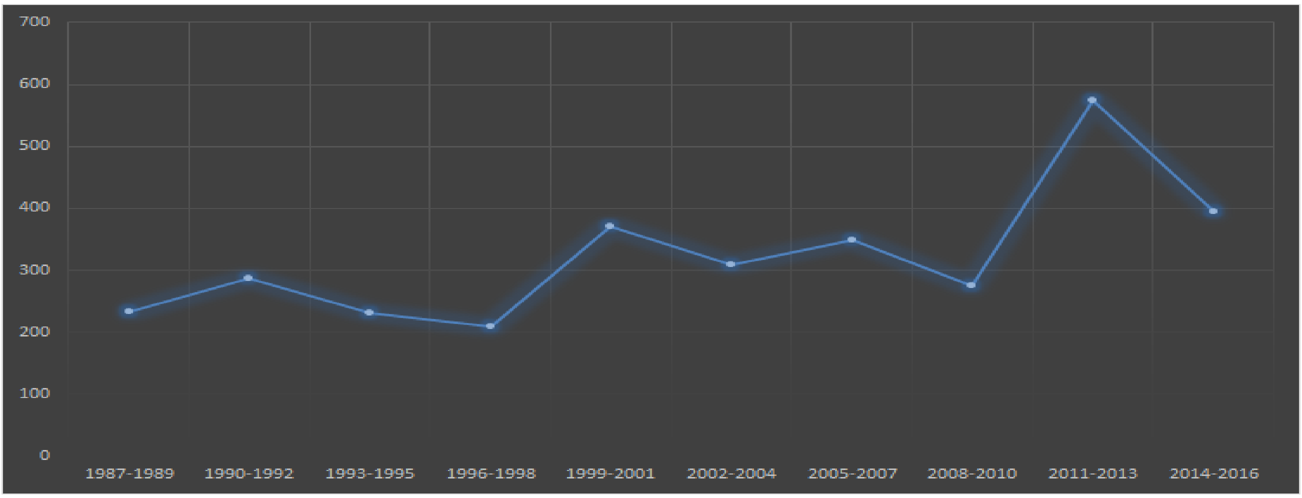
Figure 1.1. Comparing change in output per hour of UK economy (resource: Chartered Institution of Building, 2016)



Robots and robotics in construction

Robotics has been introduced into the construction industry as a solution to the problem since the 1960s. The first construction robots were designed at the early 1970s to enhance the quality of modularized homes in Japan. In the 1980s the first onsite construction robot appeared (Bock, 2006). Since the 1980s, the related research has also boomed. Figure 1.2 indicates that the number of ISARC (International Symposium Automation and Robotics in Construction)[1] papers has increased remarkably since the 1980s.

Figure 1.2. The numbers of papers in the ISARC proceedings on the three-year basis (source: own illustrated, data from 'I.A.A.R.C. - International Association for Automation and Robotics in Construction', n.d.)



[1] The ISARC is the only conference concerning the field of construction robotics and automation, held by IAARC (International Association of Automation and Robotics in Construction). The first symposium was held in 1984.

Box 1.1 Robot and robotics

'Robot' is not a word with a long history. It came from the play 'Rossum's Universal Robots' (Figure 1.2), written by the Czech writer Karel Capek in 1921 (Freedman, 2011). The word 'robota' in Czech means 'forced labor', and it was introduced into English with this science fiction play (Bould, 2010).

Although the word 'Robot' is quite new, the concept of the man-made creature has already existed for a very long time. The earliest recorded robot that can be found may be Talos, the super-nature creature in Greek mythology. It is an automaton made by bronze to protect Europe (Tzafestas, 2015). In multiple ancient cultures, scientists made automated machines, which are the prototypes of the modern robots. For instance, Da Vinci's knight (Figure 1.3 a), Al-Jazari's floating orchestra (Figure 1.3 b), and Vaucanson's digesting duck (Figure 1.3c) (Evan Andrews, n.d.).

Figure 1.3 Rossum's Universal Robots (source: Capek, 2014)

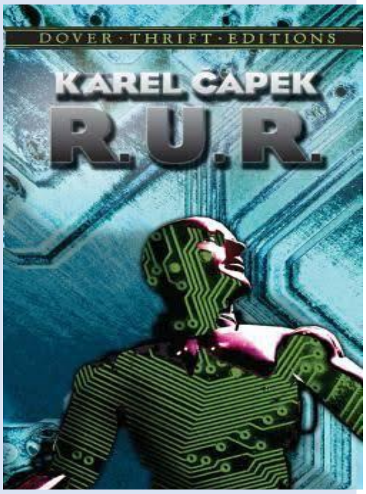


Figure 1.4. Robots in ancient times (source: Evan Andrews, n.d.)

(a) (b) (c)

There is not a universal definition of a robot, and different institutions and individual researchers give different definitions of the robot (Tzafestas, 2015). However, Nocks (2007) points out that all the definitions have mentioned a key feature of robots: a robot is a machine that can intelligently connect perception and action with the aid of embodied program, and can work without human intervention.

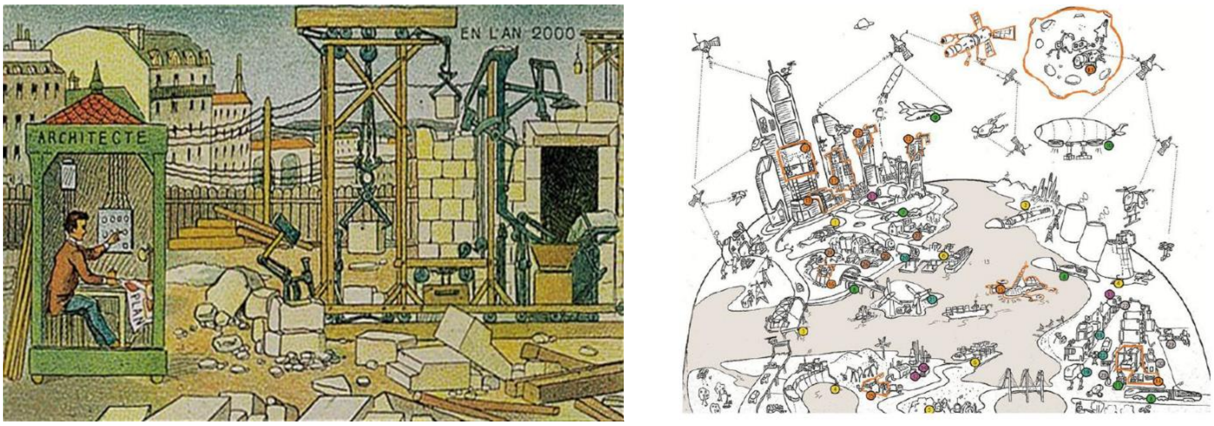
The concept 'robotics' originates from the word 'Robot'. As robots are understood as 'man-made creature which can execute works automatically', it is a natural thought that they could be used to replace human labors in producing activity. The use of robots in a specific field is defined as robotics (Stevenson, 2010). In 1961, the first industrial robot was put into practice by the company Universal Automation (Tzafestas, 2015).

New evolvement in construction robotics

By reviewing the papers of the ISARC proceedings, two trends could be observed. The first one is that the construction robotics is expanding its concerns. Previously, construction robotics mainly focused on the 'real works', which directly produce the physical products (namely the built environments), for instance, concrete polishing, curtain wall installation, and painting. (Bock, 2016). Nowadays, however, construction robotics is paying more attention to some 'invisible' tasks, such as site planning and management, sensor data acquisition and processing, logistics optimization, etc. These tasks do not directly generate the final built environments but lead to a better construction process. In this research, these works are defined as the 'second type', while those 'visible' tasks as the first. Therefore, the first trend could be rephrased as follows: the interests of construction robotics is expanding from the first type of works to the second.

The second trend is that many new technologies are appearing in construction robotics. In the 1980s and 1990s, most of the technologies in construction robotics belong to mechanical, engineering and control fields; after entering the 21st century, many new technologies have been employed in construction robotics, for instance, laser scanning, virtual reality, mobile computing, etc. Some of these technologies have already been widely applied; some others are just emerging (Oesterreich & Teuteberg, 2016).

Figure 2.4. a. The 1910's vision of a construction site in 2000 by Villemard (source: Wade, n.d.)
b. The vision of robotics and automated construction today (source: Bock, 2014)



The two pictures in Figure 2.4 partly demonstrate the trends. Figure 2.4 (a) is a postcard in the year 1910, picturing the 'future' construction site imagined by people then, focusing on replacing human workers with machines. In the new era, however, the term 'robotics' has new connotations, including not only the physical robots and machines but also their integration and networks, involving more technologies and tasks, as shown in Figure 2.4 (b).

Problem

Characterized by expanding concerning fields and the emergence of new technologies, the full picture of the technological innovations in the construction industry is becoming more and more complicated. With such a background, an overview of the available technologies is needed, so that the researchers, as well as the practitioners in this field, could quickly get an overall image of state of the art in construction robotics. However, hardly an overview of the existing technologies in construction robotics is available by the year 2017. Most of the available publications focus on specific technologies, instead of revealing a full picture.

Besides, no study has tried to explore the future landscape of construction-robotic technologies, causing difficulties in deciding the directions for research and development (R&D) activities in construction. Also, without a future picture of the technologies, the practitioners are not confident enough in choosing technical directions to invest (e.g. purchasing related equipment and training employees for a specific technology) (Oesterreich & Teuteberg, 2016).

1.2 Research questions and deliverables

This research tries to depict a full picture of robotic technologies' application in the construction industry and to explore the possible future landscapes of construction-robotic technologies. For the research of the future landscape, the time horizon is set at 2030. Too far future is impossible to explore and therefore meaningless, meanwhile too near future will not be very different from the current situation. A period of 10 to 15 years is a proper time horizon (Lindgren & Bandhold, 2002). The research is restricted within the Netherlands because all the participating experts are from the Dutch construction industry.

The main research question is:

In the Dutch construction industry, what technologies are available to enhance the robotics level and what are the possible futures of technical innovations in construction robotics in 2030?

This main research question is supported by three sub-questions.

Sub Question 1: What is the state of the art of construction robotics?

The answer to this question is the base of the research. This question identifies the tasks and technologies that construction robotics concerned, verifies the evolvement trends in construction robotics, and explores the pattern of the technologies' application in different construction tasks. The outcomes of this sub-question provide inputs for the research of the following two sub-questions. The main method to answer this sub-question is a systematic literature review.

Sub Question 2: Currently, what technologies are available to enhance the robotics level in the Dutch construction industry?

This sub question explores the currently applied and emerging technologies in construction robotics. The outcome is used as input for the future study in the next step. This sub-question is mainly answered by detailed literature study. Expert interviews are conducted to attach the literature study to the Dutch practice.

Sub Question 3: What are the possible landscapes of construction-robotic technologies in the Netherlands in 2030?

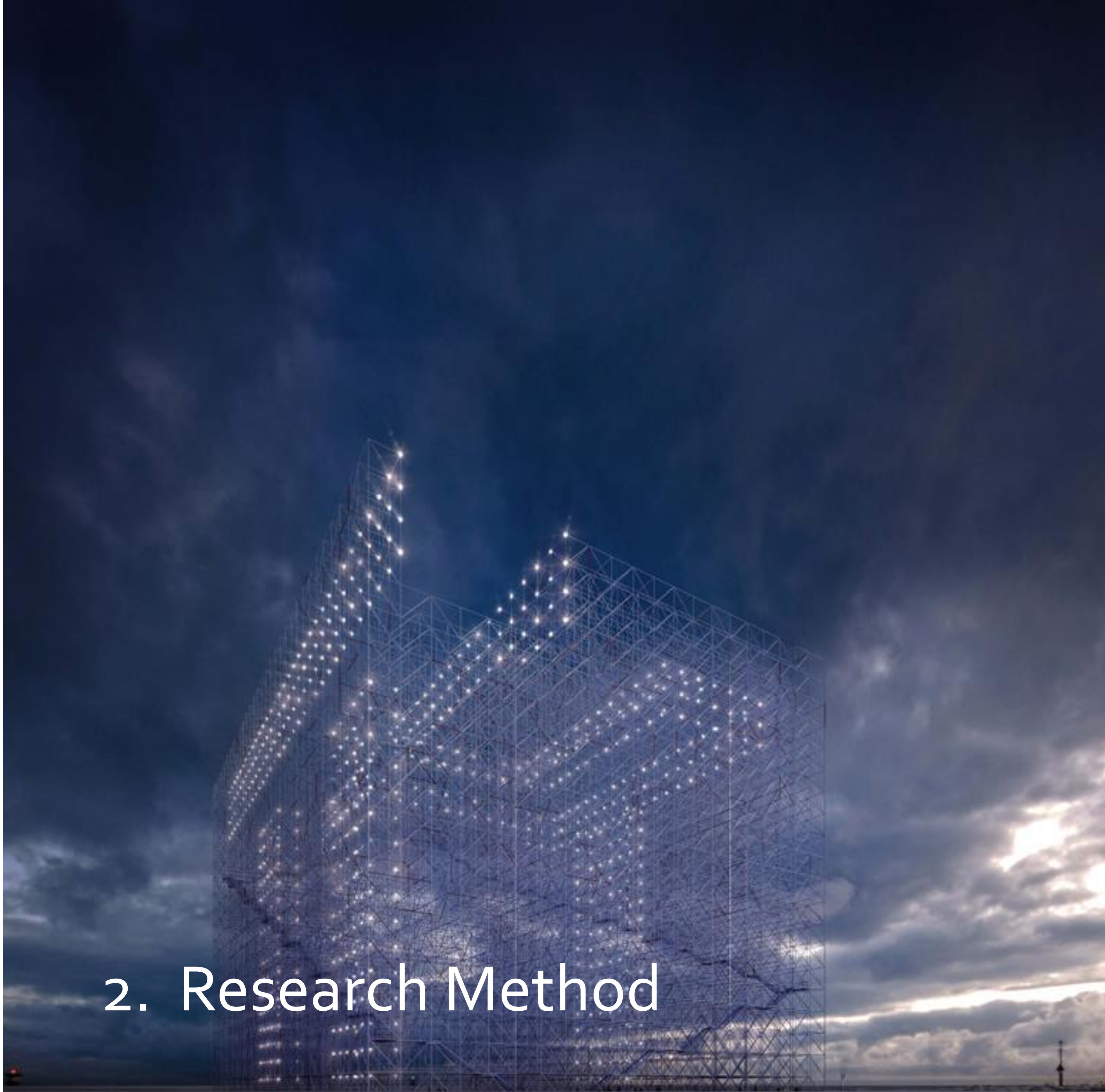
The research of this question depends on a scenario-planning based method, involving expert interviews and literature study. The method is elaborated in Chapter 2.

The research intends to provide two final products: an overview of the currently available technologies and a set of scenarios of the future landscapes in construction robotics technologies.

As the time for this research is limited, it is impossible to examine through the whole construction industry. Selecting a few specific tasks to study in detail is more realistic. The selection is discussed in Chapter 3.

1.3 Structure of the report

In chapter 2, the research methods are elaborated. Chapter 3 explores the state of the art of construction robotics by systematically reviewing related literature. Chapter 4 summarizes the currently available and emerging technologies that could be employed to enhance construction robotics in the selected tasks. Chapter 5 concludes the outcomes of the future study, revealing the possible future of the robotics development in the selected fields. Chapter 6 recaps the results of the previous chapters, and in Chapter 7, a reflection of the research is made.



2. Research Method

Key Points

- The first sub-question (the state of the art of construction robotics) is answered by systematic literature review.
- The second sub-question (the currently available technologies in construction robotics) is answered by detailed literature study, combined with expert interviews to complement the literature study.
- Scenario planning is employed to manage the uncertainties in the future study, to answer the third sub-question. The question is answered in three steps. First to identify the most relevant factors that may affect the future development of the construction-robotic technologies and establish the scenario matrix. Second, discuss the scenarios with experts to make narratives for the scenarios. Third, analyze the evolvements of the existing technologies in different scenarios to depict the possible future landscapes.

2.1 The state of the art of the construction robotics

This part depends on a systematic literature review. It is mentioned in Chapter 1 that by reviewing the ISARC papers from the 1980s to 2016, two trends in construction robotics research could be observed: the first is more tasks are concerned by construction robotics (more tasks), and the other is more technologies are employed in construction robotics (more technologies). According to these two perceived trends, the research of the state of the arts in construction robotics includes the following four topics:

- To identify the tasks concerned by construction robotics;
- To identify the available technologies in the construction robotics;
- To verify of the two perceived trends in construction robotics;
- To identify the pattern of the technologies' application in different construction tasks.

From 2012 to 2016, ISARC proceedings include 572 papers, of which 278 are about specific technologies' application in construction to improve the performance of the building activity. These papers are classified according to the tasks and technologies that they discuss, to identify the lists of tasks and technologies that concerned by construction robotics.

With the identified lists of tasks and technologies as frameworks, the previously mentioned new trends in construction robotics (more tasks and more technologies) could be quantitatively verified.

Finally, by mapping the ISARC papers in the Technology-Task Matrix (Figure 2.1), the pattern of technologies' application in different tasks could be identified, revealing which technologies are likely to be employed to assist which tasks.

Figure 2.1 The Technology-Task Matrix

	Tech 1	Tech 2	....	Tech n
Task 1				
Task 2				
....				
Task n				

2.2 Currently employed and emerging technologies

This question will be answered by detailed literature study and expert interview.

A detailed literature study is employed to examine the currently applied and emerging technologies in the selected tasks, including their working principles and added values. Then expert interviews are conducted to investigate their current applications in the Dutch construction industry, as well as the drivers and barriers of their application.

2.3 Possible landscapes of technical innovations in construction robotics in 2030

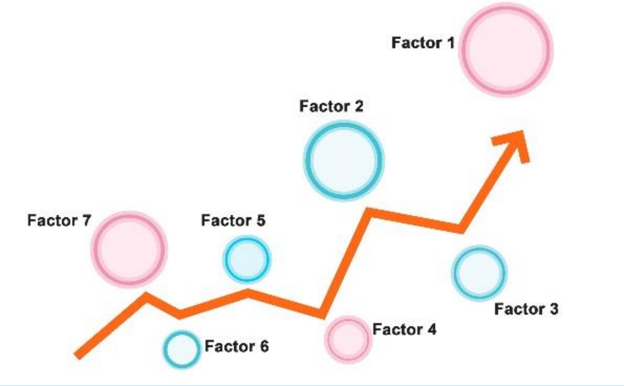
In this part, a scenario-planning based method is applied. Generally, with stable conditions and short timeframes, forecasts are employed to predict the future. However, the further ahead it is looked, and the more complex the systems are, the more irrelevant the forecasts become. In this research, the time horizon is 2030, 13 years ahead, and many factors are influencing the development of the innovations in construction robotics. Therefore, it is needed to prepare for not one but many possible futures (Lindgren & Bandhold, 2002), each of which is a different scenario. Scenario planning could be employed to reduce uncertainties to a handful of plausible alternative directions that together contain the most relevant uncertainty dimensions (Lindgren & Bandhold, 2002).

Box 2.1 Scenario planning

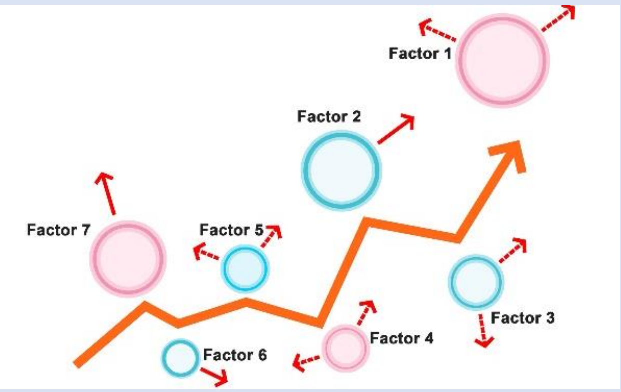
How does scenario planning manage the uncertainties

In future studies, the development of the targeted object in the future is affected by various factors (Figure 2.2 a). Some of these factors have certain development trend in the timeframe of the research, while some others, however, do not (Figure 2.2 b).

Figure 2.2 (own. ill) a. Factors affecting the future development
b. The developments of some factors are certain, some others uncertain.



(a)



(b)

These factors bring uncertainties to the future development. To manage the uncertainties, these factors will be assessed to evaluate their impacts and predictabilities in the future, then mapped in an Impact-Predictability matrix (Figure 2.3).

Figure 2.3 Factors assessment (source: own ill.)

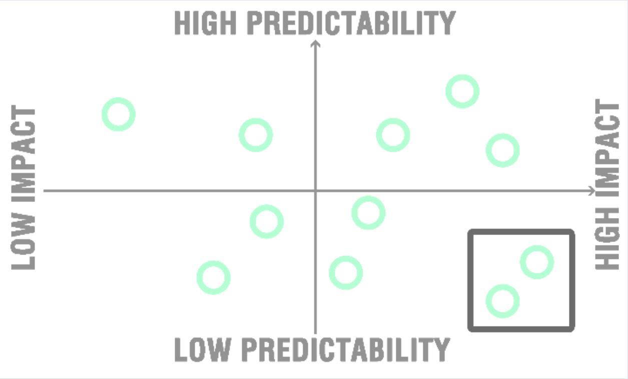
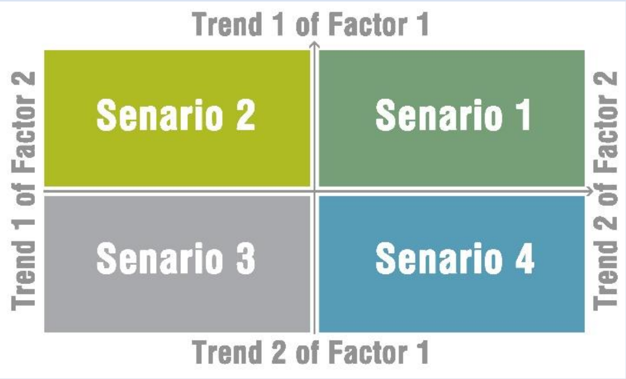


Figure 2.4 Scenario planning (source: own ill.)

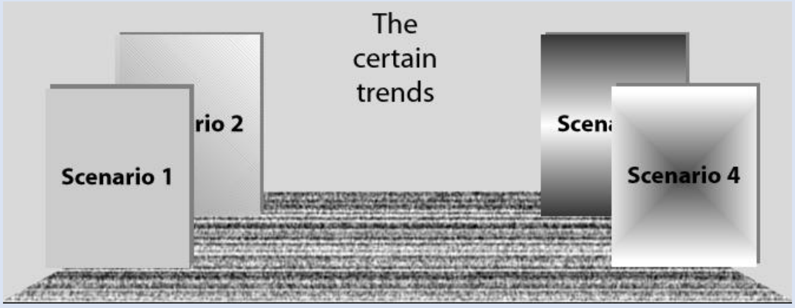


Then the two factors with the highest impact and highest unpredictability will be selected to formulate a matrix (Figure 2.4). Each of the four quadrants represents a scenario, and these four scenarios cover the most relevant uncertainty dimensions.

Why factors with low predictability

The purpose of establishing scenario matrix is to manage the uncertainties in the future. The factors with high predictabilities do not need to be considered in scenario planning phase because they do not bring many uncertainties, but certain trends. The relationship between certain trends and scenarios is illustrated in Figure 2.5, which could be compared to a play at a theater. The certain trends and their development can be compared to the back of the stage created for a certain play, while the different scenarios can be seen as specific scenes that form the background of the different acts (Lindgren & Bandhold, 2002).

Figure 2.5 The relation between scenarios and certain trends compared with a play in the theater (Source: Lindgren & Bandhold, 2002, page 64)



A three-step-method will be applied to explore the possible evolvements of the technologies in the future. In the first step, a set of scenarios of the future world will be constructed, using two key factors that may affect the evolvements of technical innovations in construction robotics. In the second step, currently available technologies' future developments in different scenarios are discussed to depict the possible future picture for each scenario. The third step is to compare the different scenarios and figure out their overlap, which is the most solid field to invest.

Step 1: Factors identification

It has been mentioned that the scenario planning depends on the factors affecting the future development of the technical innovations in construction robotics. Experts are interviewed separately to talk about the possible factors, then a list of factors is generated from the inputs. After that, all the participants are required to fill an online questionnaire, to score their impacts and predictabilities. With the two key factors with high impacts and high uncertainties, a scenarios matrix could be constructed.

Step 2: Making scenarios narratives

Mutual interactions exist between the factors identified in step 1. In each scenario, by analyzing these factors' developments and their interactions, the framework of different scenarios could be established. Expert interviews are conducted to generate more inputs to make narratives for the scenarios.

Step 3: Evolvement analysis

For a specific technology's implementation in practice, drivers and barriers exist. They are discussed with the experts in the interviews. In different scenarios, they are affected differently, and therefore, the technology's application may evolve along different paths (Figure 2.6). In this step, the interactions between the scenarios and the drivers/barriers are discussed to infer the future development of each technology in different scenarios.

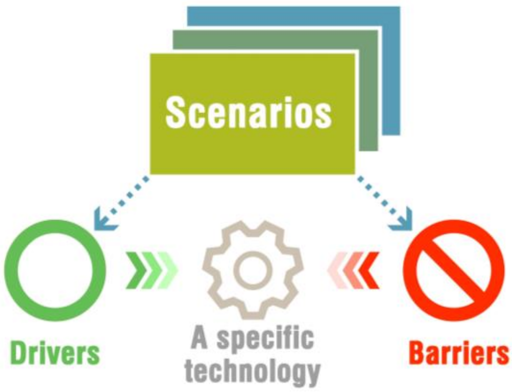
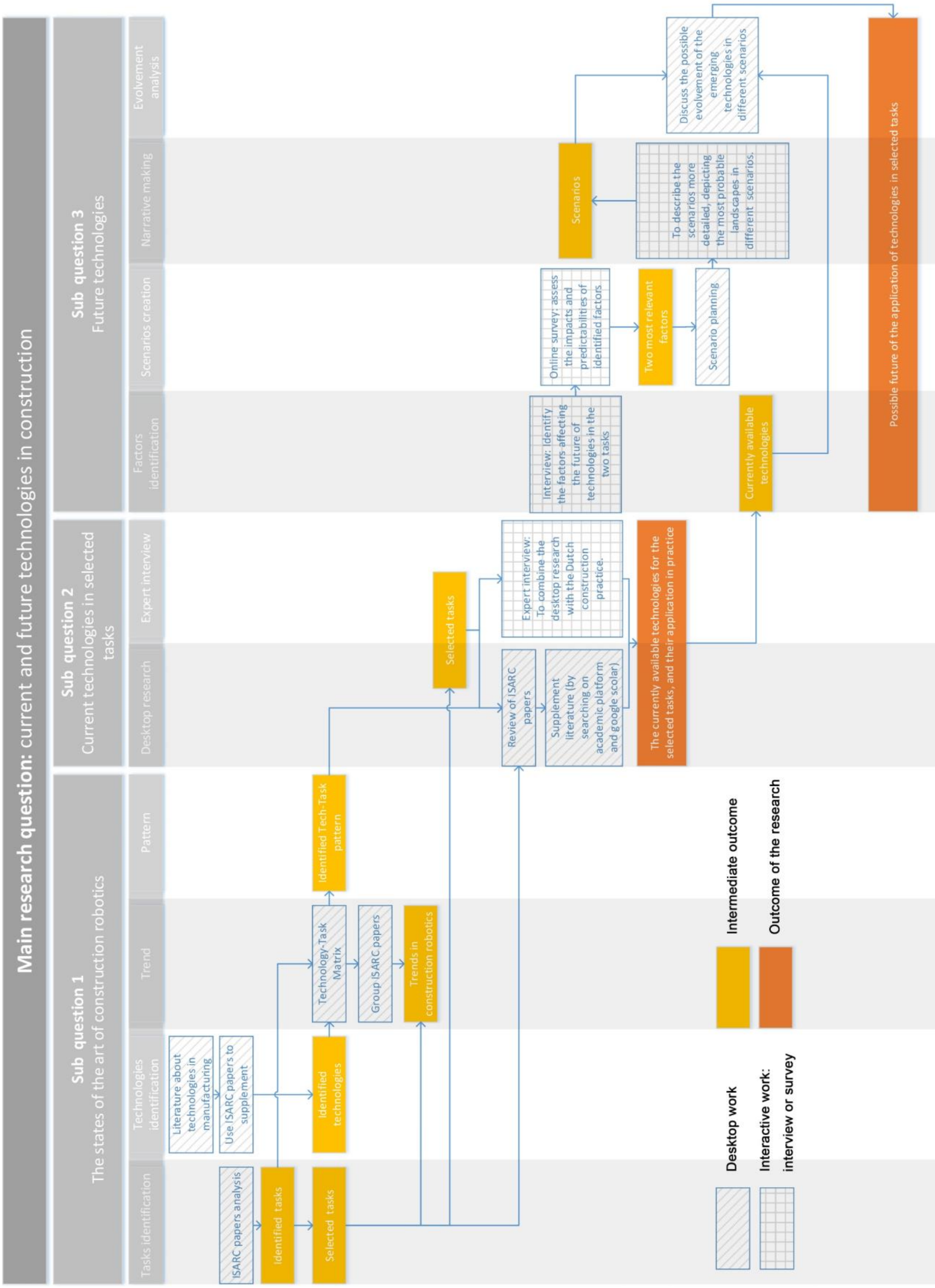


Figure 2.6 The analysis of specific technologies evolvement in the future

The research model is illustrated in Figure 2.7.

Figure 2.7 Research model



3. The state of the art of the construction robotics

Key Points

- Sixteen construction tasks are concerned by construction robotics.
- Eleven categories of technologies are employed by construction robotics.
- The two perceived trends (more tasks and more technologies in construction robotics) are confirmed by systematic literature review.
- Most of the studies in construction robotics focus on the second type of works. Among the first type of works, construction robotics concerns most the earthwork and assembly works; while the most concerned second type of works includes site management, safety management, and process management. The most frequently employed technologies are Automation and Robot, BIM, Software and Algorithm, CPS/IoT. The latter three are related to the new trends of informatization and intelligentization.
- Construction Assembly and Construction Safety Management are selected to be studied in detail.

3.1 Concerned tasks and technologies

It is mentioned in Chapter 1 that the tasks concerned by construction robotics could be classified into two types: the first type of works refer to the tasks that produce built environments, while the second do not directly generate physical environments, but help to improve the construction processes. By systematically reviewing the papers from ISARC proceedings since 2012, 16 construction tasks are identified. Ten of them belong to the first type, and the other six belong to the second. The identified tasks are illustrated in Table 3.1.

Table 3.1 The tasks concerned by construction robotics

Identified tasks in the onsite construction work	
Cluster	Tasks
First type: directly related to the physical production	Earthwork
	Reinforcement
	Paving
	Concrete distribution
	Concrete finishing
	Welding
	Coating
	Assembly
	Interior finishing
	Masonry
Second type: related to the construction process	Surveying and monitoring
	Logistics
	Site planning and management
	Safety
	Quality control
	Process management

3.2 Identification of technologies

By the year 2016, there is no literature available providing an overview of the technologies in construction robotics. An alternative way is to learn from the manufacturing industry. Many innovative technologies in construction are introduced from the manufacturing industry (Jørgensen & Emmitt, 2008). In recent years, the term of Industry 4.0 is used as a concept representing the new development in manufacturing, and it is reasonable to use Industry 4.0 technology as a benchmark to identify the technologies in the construction industry.

Oesterreich and Teuteberg (2016) have done some studies to explore the Industry 4.0 technologies in construction. They searched publications labeled with the keywords 'Industry 4.0' and 'construction', and conducted content analyses to the findings to summarize the most mentioned industry 4.0 technologies in construction, as shown in Table 3.2.

Table 3.2. The most mentioned Industry 4.0 technologies (Resource: Oesterreich & Teuteberg, 2016)

Clusters	**Industry 4.0 technologies and concepts in the context of construction**
Smart factory	Cyber-physical systems (CPS)/ Embedded systems
	Radio-Frequency Identification (RFID)

	Internet of Things (IoT)/Internet of Services (IoS)
	Automation
	Modularization/Prefabrication
	Additive manufacturing
	Product-Lifecycle-Management (PLM)
	Robotics
	Human-Computer/Robots Interaction (HCI/HRI)
Simulation and modelling	Simulation tools/Simulation models
	Building Information Modelling
	Augmented/Virtual/Mixed Reality (AR/VR/MR)
Digitalization and virtualization	Cloud Computing
	Big Data
	Mobile computing
	Social media

Then the ISARC papers are classified according to the technologies they discuss. It turns out that the list in Table 3.2 covers almost all the hot points in construction robotics, except for laser scanning.

Some items on the list are similar, or belong to the same technical family, for instance, cyber-physical system and Internet of Things. To simplify the research, some items are combined, and the final identified technologies are listed in Table 3.3. The application of these technologies is briefly introduced in Appendix A.

Table 3.3. Identified technologies

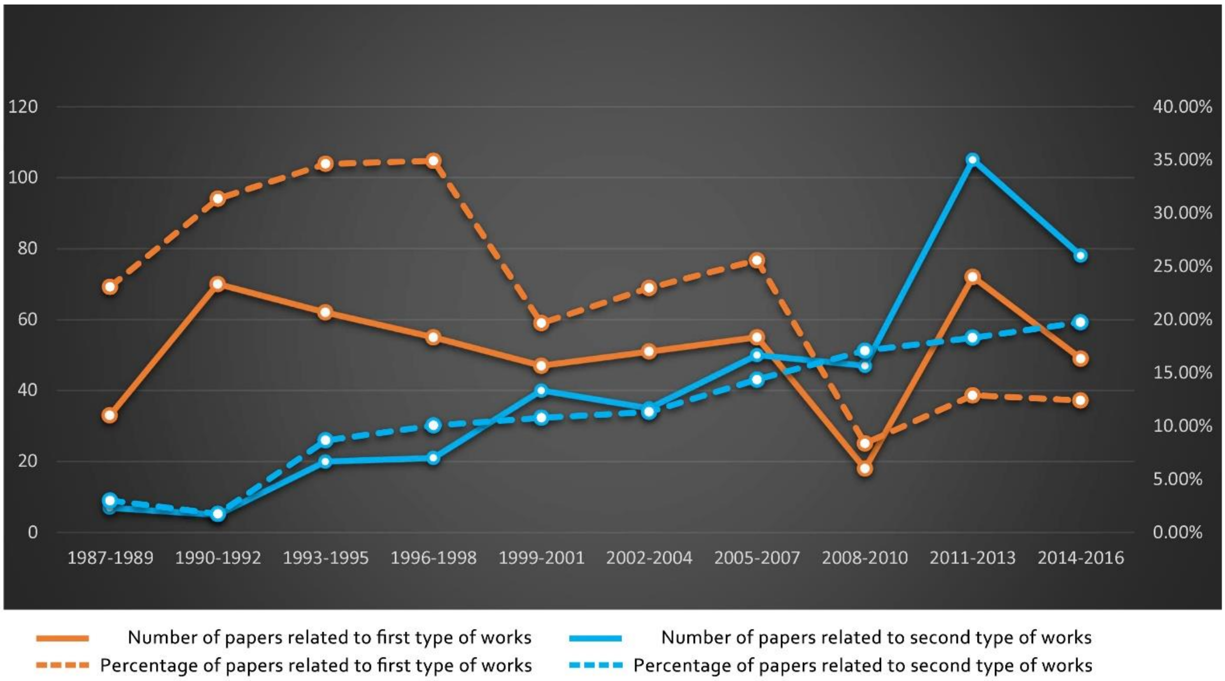
Technology	Abb.	Icon	Technology	Abb.	Icon	Technology	Abb.	Icon
Internet of Things	IoT		Human-Computer/Robot Interaction	HCI /HRI		Simulation and Algorithm	S&A	
Additive Manufacturing	AM		Laser Scanning and Photogrammetry	L&P		Cloud Computing	CC	
Modularisation and Prefabrication	M&P		Virtual Reality /Augmented Reality	VR /AR		Big Data	BD	
Automation and Robot	A&R		Building Information Modelling	BIM				

3.3 The trends in current construction robotics research

The first trend: expanding from the first to the second type of works

Figure 3.1 shows the numbers (continuous line) and percentages (dash line) of the papers related to the two type of works in ISARC proceedings on a three-year basis. It can be observed that in recent years, the percentage of articles related to the first type works is decreasing, from the highest point 30% to the current level of slightly higher than 10%. Meanwhile, the papers related to the second type of works have increased to 20% from less than 5%. These numbers imply an expansion of the enthusiasm from the first type of works to the second. Some other studies, e.g. Son, Kim, Kim, Han, & Kim (2010), obtained similar conclusion after examining the related papers in recent years in the field of construction industry.

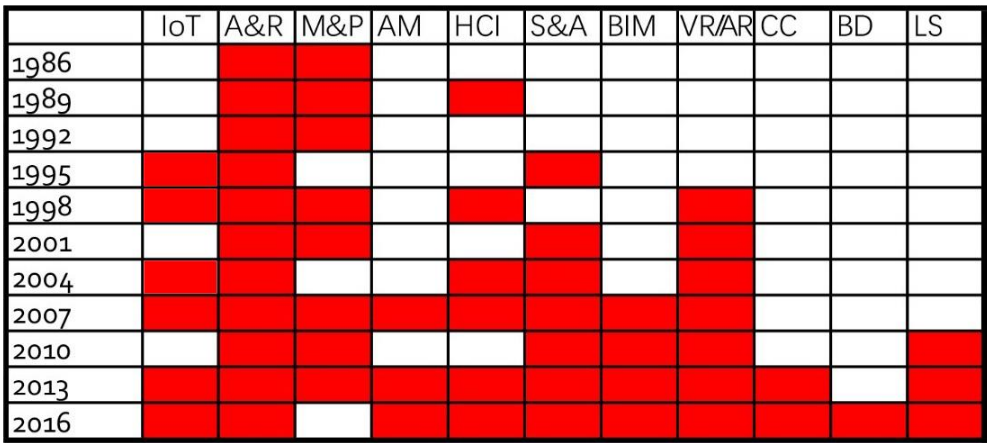
Figure 3.1 The numbers and percentage of papers related to first and second types of works in ISARC proceedings (source: own illustrated)



The second trend: more technologies involved

Figure 3.2 illustrates the appearance of different technologies in the ISARC proceedings since the 1980s. It could be easily observed that more and more technologies are emerging in construction robotics field, help to improve the performance of the industry.

Figure 3.2 The technologies involved in ISARC proceedings in different years (Source: own ill.)



To sum up, the trends perceived previously are confirmed by the systematic literature review. Construction robotics is expanding its interests from the first type of works to the second type; simultaneously, new technologies are introduced into construction to fulfill the demand in the construction industry. These two trends should be considered in the selection of the tasks to be further studied in this research.

3.4 The pattern of technologies' application in construction robotics

Papers from the proceeding of ISARC in the recent five years are examined to see researchers' interest in construction innovations. In the last five years, the proceedings of ISARC have 572 papers, within which 271 papers are related to the application of technologies in construction. The distribution of the papers in the Technology-Task Matrix is illustrated in Table 3.4.

Table 3.4. The distribution of related papers in the Technology-task matrix

	IoT	A&R	M&P	AM	HCI	S&A	BIM	VR/AR	CC	BD	L&P	other	total
Earthwork	3	7	0	0	0	3	3	0	0	0	1	9	27
Reinforcement	0	1	0	0	0	1	2	0	0	0	0	0	4
Paving	0	0	0	0	0	0	0	0	0	0	0	1	1
Concrete distribution	0	0	0	0	0	0	0	0	0	0	0	0	0
Concrete finishing	0	1	0	1	0	2	0	0	0	0	0	1	5
Welding	0	0	0	0	0	0	0	0	0	0	0	0	0
Coating	0	5	0	0	0	0	0	0	0	0	0	0	5
Assembly	1	6	1	0	0	3	1	1	0	0	2	3	18
Interior finishing	2	1	0	0	0	0	0	0	0	0	1	0	4
Masonry	0	1	0	0	0	0	1	0	0	0	0	0	2
Surveying and monitoring	9	4	0	0	0	2	2	0	1	0	3	4	26
Logistics	2	4	0	0	0	11	2	0	0	0	1	4	24
Site planning and management	6	1	0	0	0	10	5	1	0	0	5	6	36
Safety	7	4	0	0	0	7	2	3	1	3	1	15	43
Quality control	0	2	0	0	0	0	1	0	0	0	6	4	13
process management	3	2	0	0	1	9	4	1	2	0	1	10	37
other	1	6	0	2	2	1	5	3	1	0	2	0	26
total	34	45	1	3	3	49	28	9	5	3	23	57	271

It could be concluded that the research in robotics of the second type of works is much more active than that of the first type. Within the 271 papers in the table, 66 are about the first type of works. Meanwhile, 179 papers discuss the second type. The most concerned first type of tasks are earthworks and assembly works, with 27 and 18 papers concerning respectively. The most focused second type of works is safety management, site planning and management, and process management. The numbers of papers related to the three topics are 43, 36 and 37 respectively.

From the perspective of technology, the 'traditional' robotic technologies, namely the automation and robots, still take a considerable share of the research activities, and they are employed mainly in the first type of works. Other popular technologies include those related to informatization (software and algorithm, BIM) and intelligentization (CPS/IoT) of the construction industry.

The pattern illustrated could be used as a framework to investigate the technologies in the selected tasks.

3.5 Construction tasks selection

As mentioned previously, a few construction tasks will be selected to study in detail due to the time constraint of this master project. Considering the trend that the construction robotics is expanding its focus from the first type of works to the second, two tasks will be selected, one from each.

Four criteria are considered in the selection process.

- The extent to which the task is executed onsite. Compared with the offsite work, onsite works suffer more from the dynamic working environment, contributing to the low robotics level in construction (Feng, Xiao, Willette, & Mcgee, 2014; Zhai et al., 2014).
- Concerns of academia. Interests to a specific area from the academic circle indicate that the field is a hot point

and thus, more literature is available. The number of papers in a specific field could be used as an indicator for this criterion.

- Technology involvement. The purpose of this research is to figure out the currently used technologies and the possible future of the technologies' application in the selected tasks. Tasks with more technologies involved have higher priorities to be studied.
- Connection to the Dutch construction practice. This research focuses on the construction practice in the Netherlands. Therefore, the selected tasks should be more closely related to and concerned by the Dutch construction industry.

The final selected tasks are **construction assembly** and **construction safety management**. The selection method and process are illustrated in Appendix B.

4. Current Technologies

Key Point

- The process of construction assembly works can be divided into four steps: Identifying, Conveying and aligning, Connecting, and Inspecting.
- The technologies employed in each phase are illustrated in the following table.

Phases/steps	Technologies
Identifying	Wireless sensing (CPS/IoT), BIM
Conveying and aligning	Handling robots/robotic systems (A&R), Single task robots (A&R), Human-Robot Interface (HCI/HRI), Virtual Prototyping (S&A), BIM
Connecting	Single robots (A&R), Augmented Reality (AR/VR/MR)
Inspecting	Laser scanning (LR), BIM

- Technologies employed in construction assembly could be divided into four clusters. The first contains those 'traditional' mechanical robotic technologies, including single-task robots, handling robots/robotic systems, and human-robot interface. These techniques are still playing an important role in construction assembly, mainly in the conveying and aligning phase and connecting phase.The second cluster includes a series of ICT technologies, which are employed to control and manage the process of construction assembly works. The third cluster refers to those technologies that collect information (Internet of Things, laser scanning) and display information (IoT, VR, AR, Cloud computing). Finally, integrated building systems are applied to assist the whole process of construction assembly (onsite Construction Factory, Bottom-up System).
- Construction safety management could be categorized into five types: safety training, safety planning, hazards alarming, proximity detection, and gesture monitoring.
- The technologies involved in each category are illustrated in the following table:

Categories	Technologies
Safety training	Virtual Reality (AR/VR/MR), BIM
Safety planning	Virtual Prototyping (S&A), Virtual Reality (AR/VR/MR), BIM
Hazards alarming	Wireless sensing (CPS/IoT), Augmented Reality
Proximity detection	Wireless sensing (CPS/IoT)
Gesture monitoring	Wireless sensing (CPS/IoT), Big Data

- The essence of construction safety management is to manage the information of the hazards. Therefore, most of the involved technologies are information-related.

4.1 Technologies in construction assembly

Construction assembly is the process of integrating the separated building materials or prefabricated components into whole structures (Chudley & Greeno, 2013). In this research, the term 'assembly work' excludes the building activities using primary materials to construct, e.g. the masonry works, mainly focusing on the integration of prefabricated components, including the assembly of structural systems, MEP systems, wall systems, etc. To assist describing the technologies for construction assembly, the assembly process is divided into four steps, as shown in Figure 4.1. The division of the steps is concluded by reviewing the related literature.

- Identifying: to locate and pick out the targeted components or units from the stock yard;
- Conveying and aligning: to send the components or units to the final position and refine the position;
- Connecting: to connect the components or material to the existing structures;
- Inspecting: to check whether the assembly works have been done in compliance with the design.

The technologies which are available in construction-assembly works will be presented according to the working process.

4.1.1 Identifying

Identification is to select the components that are going to be assembled from the onsite stockyard. Traditionally, this identification is managed by paper record (Roberti, 2013) – a manual process that may enable errors and take a long time to complete. Therefore, tools that could help to identify and locate the target components or materials are required (Nasr, Shehab, & Vlad, 2013).

Internet of Things (IoT)

IoTs use wireless sensing techniques (for instance Radio Frequency Identification, Ultrawide Band, Global Position System, etc.) to connect the tags and sensors attached to the targeted objects. Thus it helps to collect the information of the construction site, such as the position of the onsite materials and equipment, the working environment, and the project process. When new building materials or equipment is delivered to the sites, they are included in the IoT by scanning their tags, and the site managers know the dynamic of onsite inventory in real time. A monitorable IoT enables wirelessly identifying and locating the targeted objects from a distance (Whitelight Group, 2014).

With the assistance of IoT, the time needed to figure out the targeted components could be significantly shortened. At the same time, the possibility of mistaking building components is reduced, contributing to a lower cost of rework.

There have been some cases of application of IoT in the inventory management and object identification (Roberti, 2013). In the Netherlands, it has also been applied in some pilot projects (interview 5, 6). However, this technology has not been used widely in the Netherlands, partially caused by conservativeness (interview 5). Besides, tracking human beings is limited by law in the Netherlands right now, to some extent impeding IoT's wide implementation (interview 6).

4.1.2 Conveying and aligning

This step is to send the building components to the final position where it will be assembled, and refine the position. The traditional method is to employ tower crane in open space (Cousineau & Miura, 2008), and labor force in indoor circumstances (Pan, Bock, Linner & Iturralde, 2016). Tower cranes are slow and easily affected by the wind (Pan, Bock, Linner & Iturralde, 2016). Meanwhile, the human-based conveying increases the labor cost in construction. In the

Netherlands, legally each worker is forbidden to handle weights over twenty kilograms (interview 6). Therefore, the contractors have to hire more labors to handle the weights. Otherwise, the progress of the projects may suffer from delays.

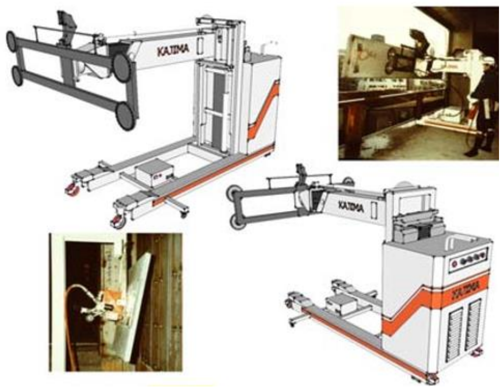
BIM and IoT

BIM and IoT could be employed to improve the conveying process. At the beginning of the conveying process, IoT locates the target objects, and BIM model provides its final position in the building. Then an optimized conveying path could be generated. The movement of the objects will be tracked and monitored. If their path deviates from the original path, a new one will be calculated according to the current position. It is expected that an automated tower crane could reduce the conveying time by 10% to 50% (Lee et al., 2009). Also, it reduces the safety risks by monitoring the moving processes. The technology is now in the experimental phase.

Handling robot/system (Automation and Robot, A&R)

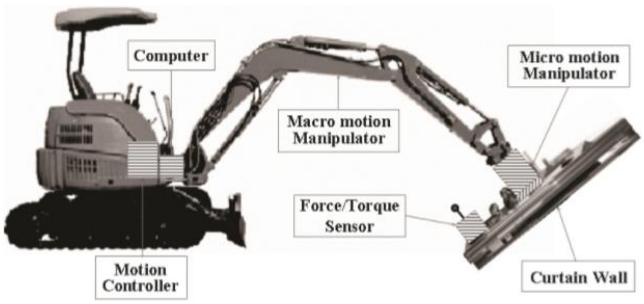
Handling robots are developed to relieve workers from heavy physical exertion. One of the examples is the 'Might Hand' by Kajima Construction (Figure 4.1), which could move heavy objects to the desired position with little manual assistance. The workers only need to do some preparation, direct the robot, off-load and position of the building materials (Pan, Bock, Linner & Iturralde, 2016).

Figure 4.1. Kajima Mighty Hand (Source: Pan, Bock, Linner & Iturralde, 2016)



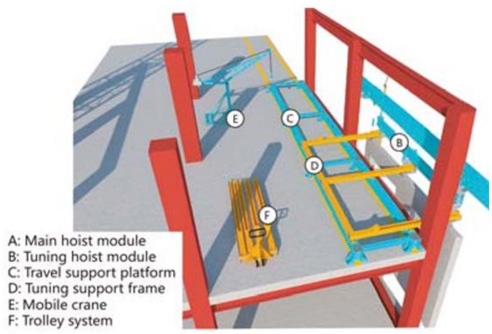
Another robot developed for handling curtainwall panel is Hybrid Curtain-wall Glazing Robot (HCGR) (Figure 4.2). It consists of a mini-excavator, which works as a macro motion manipulator, conveying curtain-wall units in long distance, and a robotic manipulating arm as the micro motion manipulator, which could adjust the position of glass panels subtly (Cousineau & Miura, 2008).

Figure 4.2. HCGR (Source: Lee & Moon, 2015)



Similar to the material handling robots, a robotic system for handling exterior wall panel has been proposed. It consists of several sub-systems, which respectively vertically lift the panels from ground floor to the working floor, and horizontally move them on the working surface, fine tune them, hold and support them before they are finally fixed (Pan, Bock, Linner & Iturralde, 2016) (Figure 4.3).

Figure 4.3 The construction material handling system proposed by Pan et.al. (Source: Pan et.al., 2016)



The system has two main advantages. The first is that it reduces the conveying time. It decomposes the conveying process into several parts (vertical lifting, horizontal moving, and fine-tuning), which could be executed parallelly. Thus, the total time consumption could be reduced. The second advantage is stability. Traditionally, the wall panels are lifted by cranes, which suffers from swaying in the lifting process. This new system holds the objects with a static steel frame before they are finally fixed, reducing the time and labor forces needed in the align process. This system is still at the stage of prototyping (Pan, Bock, Linner & Iturralde, 2016).

Handling robots/robotic systems reduce the time and labor required in the conveying processes, enhancing the efficiency in projects. Besides, it uses static frames instead of cables, to diminish sway in the process, diminishing the potential safety risks.

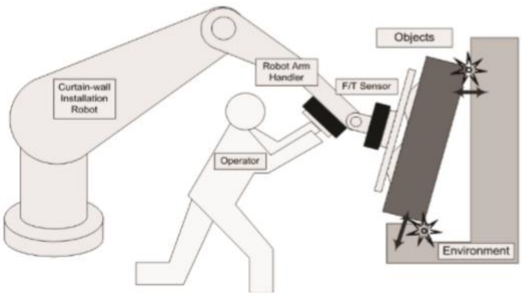
Some attempts at applying handling robots have happened in the Netherlands (Interview 5), but still not widely used, mainly because the robots are cumbersome, especially in the indoor spaces (interview 6). Fortunately, efforts are being paid to smaller and lighter handling robots (Feng et al., 2014, Interview 6). In the future, the handling robots and the robotic handling system may be combined to enhance efficiency in conveying works.

Human-Robot Interaction (HRI))

In conveying processes of building components, some works require cooperation between human labors and robots. Generally speaking, robots are good at speed, power, and precision, while human labors are more flexible and adaptable (Lee & Moon, 2015). Human-Robot Interface technologies have been applied to assist the cooperation.

Figure 4.4 shows the concept of an intelligent hybrid manipulator, which helps operators to handle objects. Sensors embedded in the manipulator can perceive the direction and angle of the operator's force and exerts an assist force in the same direction. Also, this device allows the operator to feel reaction forces from environments during an operation (Lee & Moon, 2015). Thus, the human worker and the manipulator could cooperate to handle the object with both strength, flexibility, and stability.

Figure 4.4. The concept of a hybrid manipulator (Source: Lee & Moon, 2015)



Augmented Reality (VR/AR)

AR technologies can visually superimpose the digital 3D spatial data to the real environment using mobile intelligent devices. With the information imported from BIM, AR devices show the final position and status of the to-be-assembled components to the operators on screens. This presented image could be used as an intuitive guide for the assembly tasks, and the operators do not need to check the 2D drawings. Therefore, the total assembly time will be reduced. It also helps to prevent assembling in wrong way to avoid reworks. By the year 2017, Augmented Reality has not been widely applied in the Dutch practice, although there have been several attempts (interview 6). The main obstacle to its wide application is that AR is still an expensive technology for practice; but compared with the price of AR devices at the beginning of this century, the price has considerably decreased. It could be expected that the device will be affordable in a few years, and will be widely used (interview 6).

4.1.3 Connect

After the components or materials are located in the right position, they are connected to the existing structure properly.

Single-task Robots (Automation and Robot, A&R)

Usually, this is done by bolting or welding works, which theoretically, could be executed by single-task robots. Bolting and welding robots have been applied in manufacturing for a long time, while in the construction industry, because of the uniqueness of the final product and the unstructured environment, their applications are limited (Bock & Linner, 2016; Chu, Jung, Lim, & Hong, 2013). In the Netherlands, currently, they are seldom used on the construction site (interview5, 6).

4.1.4 Inspecting

Inspecting processes check whether the assembly works have been done in compliance with the design. The inspection of construction assembly tasks is traditionally conducted manually, depending on inspectors' subjective judgments, with risks of incompleteness and inaccuracy.

Laser Scanning and Photogrammetry (L&P)

To fulfill the demand for quick and accurate project inspection, a laser-scanning based method has been introduced to automate the inspection and process assessment (Bosché, Turkan, Haas, Chiamone, Vassena & Ciribini, 2013; Ahmed, Haas & Haas, 2013). Three-dimension Laser Scanning is employed to build a digital model of the built environment in short time (Tang, Anil, Akinci, & Huber, 2015). By aligning the scans of the built environment and the 3D BIM models, the deviations could be easily identified. The new method shortens the time needed for inspection. In construction assembly tasks, laser scanning could be employed not only to assist inspections but also to monitor the assembly process, steering the deviation between 'as-built' and 'as-designed' in real time. It could be used for both structure and MEP (Mechanical, Electrical, and Plumbing) equipment assembly tasks (Bosché, Turkan, Haas, Chiamone, Vassena & Ciribini, 2013).

Photogrammetry is an alternative for laser scanning in modeling the as-built environment (Safa, Nahangi, Shahi, & Haas, 2013). Photogrammetry method uses several digital photos from different perspectives, with the help of particular algorithm, to reconstruct the 3D space in the computer.

Currently (the year 2017), the application of laser scanning in the Netherlands is rising (Interview 5, 6). Its current cost (30,000~40,000 euros) is affordable to most of the contractors (Interview 6).

4.1.5 Comprehensive systems

Besides the technologies in specific steps of the assembly process, some comprehensive systems are used to erect buildings.

Construction Factory (Automation and Robot, A&R)

In the automobile manufacturing sectors, the working environments are well structured and controlled. Thus the robotic and automatic technologies could be well applied, enhancing the efficiency, productivity, and quality (Chu et al., 2013). Compared with these industries, the construction sector suffers more from complex and unstructured working environments, which are surrounded by messy objects and various interacting tasks, impeding the application of robotic technologies. This is an important reason that the assembly work by far have been executed manually, although they are labor-intensive and sometimes dangerous (Chu et al., 2013).

To solve the problem, originated from Japan, a type of construction system named 'Construction Factory' (CF) has been developed since the late 1980s. The idea of this system is to apply the factory automation in construction, and allow the works to be done in comfortable and controllable environments (Ikeda & Harada, 2006). A CF is a factory-like structure that surrounds a building (or part of the building) and includes various robotic systems to automate construction process (Ikeda & Harada, 2006). This structure, permanent or temporary, provides an 'indoor' working space onsite, which is less likely to be affected by weather, creating a more comfortable circumstance on the construction site, thus robotic and automation technologies could be implemented as in a factory.

In Japan and Korea, some CF systems have already been applied in practice. For example, Obayashi Corporation has implemented the Automated Building Construction System (ABCS) for several times (Ikeda & Harada, 2006) (Figure 4.5).

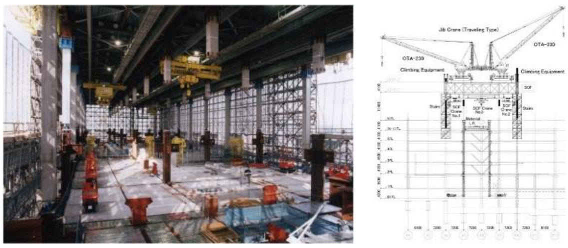


Figure 4.5. Onsite Construction Factory (Source: Chu et al., 2013)

Most of CF systems are heavy, complicated, expensive and time-consuming to install, which impede the systems from being widely used (Chu et al., 2013). Recently, a new system, which is quite slim compared with the previous mentioned, has been developed in South Korea, focusing on the steel structure assembly. It integrates the onsite construction factory, automatic conveyor, and automated bolting robotics (Chu et al., 2013). This new development indicates that this system is trying to be smaller and lighter to adapt to the demand of the market.

There are a few trials of Construction Factory system in the Netherlands, for instance, in the project Rotterdam Medical Center (Figure 4.6). However, it is not widely employed in the Netherlands (Interview 5, 6). The system is proper for high rise buildings with many standard floors, which are less popular in the Netherlands (Interview 6).

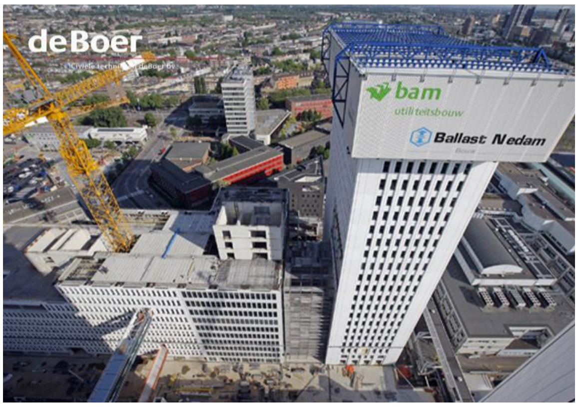


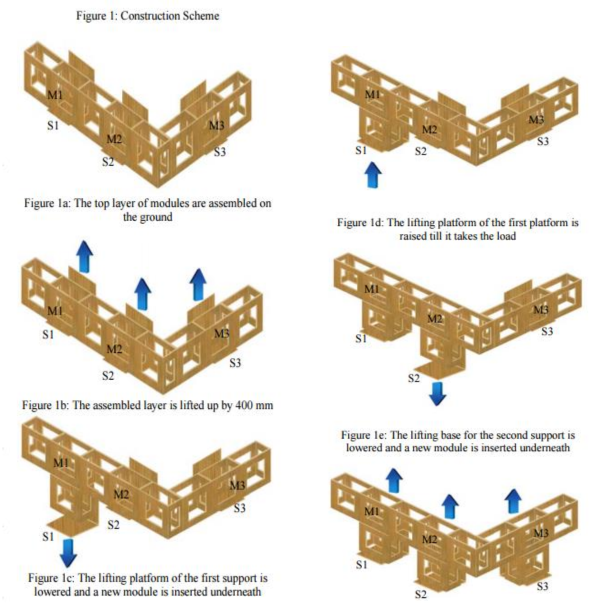
Figure 4.6 The Construction Factory system in the construction process of Rotterdam Medical Center (Source: Holmatro, 2017)

Bottom-up construction system (Automation and Robot, A&R)

In historic urban areas, construction sites are congested, without enough space for installing heavy equipment. To overcome that, a system has been proposed, which could assemble the components without using large facilities (e.g. tower crane) (Raphael, Rao & Varghese, 2016).

In this system, buildings are designed to be constructed with modules of the same height; the top floor will be assembled on the ground floor, then lifted by hydraulic jacks to enable the lower layer of modules to be assembled. Thus, all assembly activities are performed on the ground floor, avoiding aloft works. The working process of the system is illustrated in Figure 4.7.

Figure 4.7 Working process of the Bottom-up Assembly System (Source: Raphael, Rao & Varghese, 2016)



Adopting this system brings a few benefits. First, working space on the ground is safer and more stable, providing an environment more proper for other automation equipment. Second, the process of lifting components is

not needed anymore, the time and energy consumption
could be reduced (Raphael, Rao & Varghese, 2016).

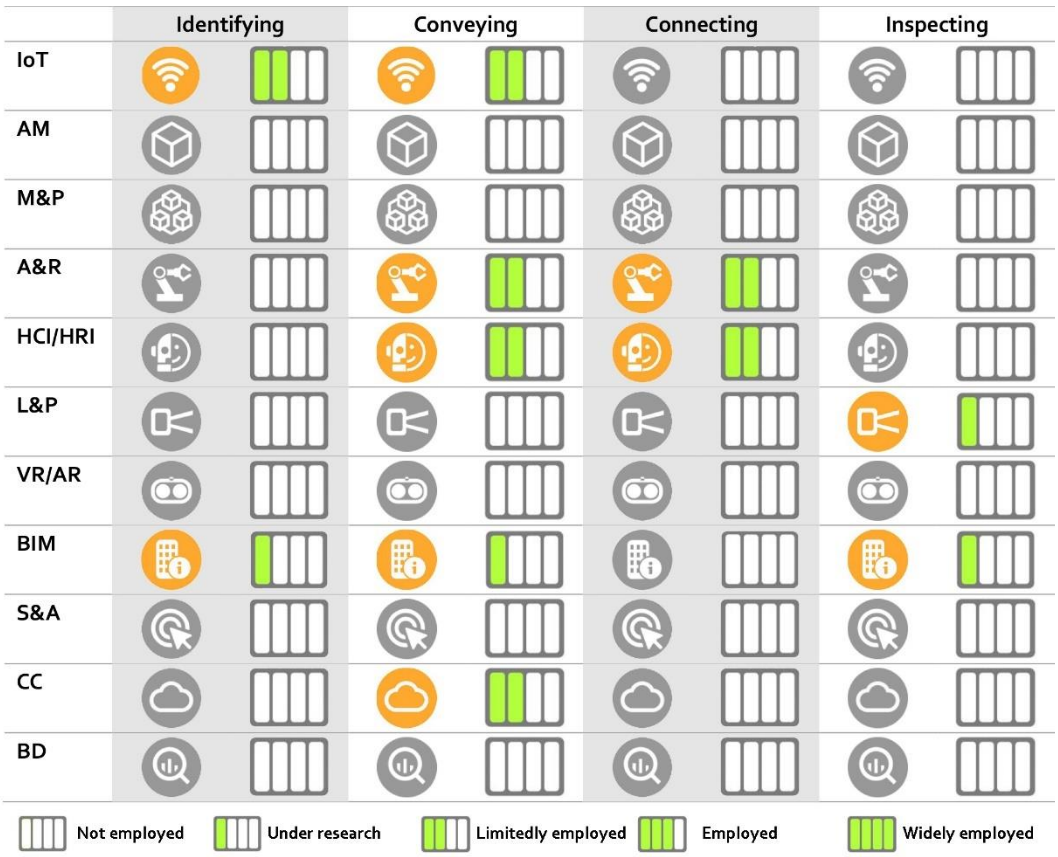
Experiments illustrate that this system can construct small buildings with significantly reduced labor and at a lower cost (Raphael, Rao & Varghese, 2016). The system is still in research and experiment stage.

4.1.6 Summary

Currently, the robotics level of construction assembly in the Dutch construction industry is quite low. Although some of the technologies identified by literature study have applied in pilot projects in the Netherlands, none of them is implemented on a large scale. Some of these technologies are both technically and financially feasible, and the most major barrier for their application is the conservativeness of practitioners and the lack of imagination (Interview 6).

Among the clusters of technologies identified in Chapter 3, six have been applied in construction-assembly works, or at the prototyping phase. These clusters include IoT, Automation and Robot (Handling Robots, Single-Task Robots/Robotic System, Construction Factory, Bottom-up System), Laser Scanning and Photogrammetry, BIM, and Cloud Computing (Figure 4.8). Details could be found in Table E.1 (Appendix E).

Figure 4.8. Technologies in construction assembly



4.2 Technologies in construction safety management

Construction took a large part of work-related-fatalities before the 21st century. The number differs in different countries, being up to more than a quarter of the fatal accidents of workers (Teizer, 2016). In EU, the fatal accidents in working conditions have decreased to below three fatalities per 100,000 employees, however, this number for the construction industry is over 10 (Eurostat, 2014). Obviously, the construction sector is a major contributor to the working accidents, causing considerable financial losses to both workers and employers, as well as the welfare system.

Onsite safety management works could be classified into the following categories (Guo, Yu, & Skitmore, 2017; Zhou, Goh, & Li, 2015): Safety training, Safety planning, Hazards alarming, Proximity detection, and Gesture monitoring.

Traditionally, safety management in construction depends on manual means, which are usually labor-intensive, time-consuming, error-prone, and inefficient (Zhang, Teizer, & Pradhanang, 2015; Teizer, 2016). For instance, in many projects, onsite observation and reviewing 2D drawings are the main methods to identify the potential risks (Rozenfeld, Sacks, & Rosenfeld, 2009; Zhang, Teizer, Lee, Eastman, & Venugopal, 2013). As a result, the safety management operations are not sufficient enough due to the subjective judgments (Zhang, Sulankivi, et al., 2015). With such a background, robotic technologies have been introduced into the construction safety management field to improve the performance.

4.2.1 Safety training

Early hazard recognition in the construction environment is important for preventing accidents. For a long time, employers in construction provide safety training to their employees to increase their awareness of the onsite hazards to improve safety performance (Sawacha, Naoum, & Fong, 1999).

Safety training consists of onsite and offsite training. Offsite training cannot provide sufficient hands-on experiences, while onsite training is inefficient (time and effort consuming), and interferes with the onsite construction work, affecting productivity negatively (Guo et al., 2017).

Virtual Reality and BIM (VR/AR, BIM)

The development of Visual Reality technologies, together with BIM as an information database, provides the trainees virtual environments for hands-on training, where the construction processes could be demonstrated vividly (Teizer, Cheng, & Fang, 2013; Hilfert, Teizer, & König, 2016). From the first-person view, workers could learn how to recognize potential hazards much more intuitively, generating more accurate reactions to emerging dangers, thus enhance the efficiency and effect of the training (Hilfert, Teizer, & König, 2016). This system could also be used to test workers' safety consciousness (H. Li, Lu, Chan, & Skitmore, 2015).

The decrease of the cost of VR equipment in recent years makes it possible to be applied in safety training for the construction workers. Some working safety and health organizations in the Netherlands, have already begun to provide the service of 'virtual onsite worker training' (Interview 5).

4.2.2 Safety planning

Safety planning is to identify the possible hazard area, including the potential falling, burning, conflicts, etc., before the construction work started. Conventionally, safety engineers do safety planning by reading 2D site layout plans. This non-intuitive method often leads to omissions (Zhang, Boukamp, & Teizer, 2015).

Virtual Prototyping (Simulation and Algorithm, S&A)

Virtual prototyping (VP) approach has been introduced to assist the identification of potential hazards (Fang, & Cho, 2016). Virtual prototyping (VP) originated from the manufacturing industry. It helps to check and validate a design before making a physical prototype. With particular software, the designers and engineers could simulate the product to test its behavior, checking whether it fulfills the designed functions. In the first decade of the 21st century, VP has been introduced to the construction industry (Huang, Kong, Guo, Baldwin, & Li, 2007), enabling the construction processes to be simulated and analyzed before the project is constructed (S. S. Kumar & Cheng, 2015). Thus, the safety risks in construction could be analyzed in advance, and the accuracy and completeness of hazard identification are improved compared with the traditional manual way.

Now in the Netherlands, VP has not been used on a large scale for safety management, although it has been employed in some other fields, e.g., energy consumption (Interview 5, 6). Simulation for identifying potential safety issues has been legally commendatory in some states of the US, but still not in the Netherlands. It is new for the safety management in the Dutch construction industry; practitioners need time to know and adopt it (Interview 6).

Virtual Reality and BIM (VR/AR, BIM)

The combination of VR and BIM technologies mentioned in the section 4.2.1 could also be employed in safety planning. Safety engineers can virtually examine the construction sites from a first-person view to identify and assess the possible safety risks. It is more intuitive than doing that on 2-D drawings, enhancing the efficiency of the work. It has not been widely used in the Netherlands.

4.2.3 Hazards alarming

Wearable devices and Wireless Sensing (Internet of Things, IoT)

Smart wearable devices can be used to avoid collisions between workers and equipment. Tags are attached to the wearable devices. When workers are approaching a specific equipment, the reader on the equipment can detect the direction and distance of the tag, and a reminder will be sent to both the operator and the worker (Choe, Leite, Seedah, & Caldas, 2014; Guo, Yu, Liu, & Zhang, 2014). Such technologies have been applied in the Netherlands (Interview 5, 6)

Augmented reality and BIM (VR/AR, BIM)

Augmented Reality (AR) and BIM could be used to warn the workers. Using the AR glasses, the identified hazardous zones, such as the spots where failings or potential collisions are more likely to happen, are visually imposed on the physical environment. Thus the workers can see these hazards intuitively to avoid them (Talmaki, Dong, & Kamat, 2010). The Dutch construction practice has not seen AR's application in safety management (Interview 5, 6), but it is technically possible and have a good prospect (Interview 6).

4.2.4 Proximity detection

Collisions between human workers and equipment contribute a major share of the fatality in construction. To detect the proximity between the objects helps to prevent collisions from happening.

Internet of Things (IoT)

The technology employed in proximity detection is IoT. Sensors or tags are placed on the objects and then tracked using wireless location sensing techniques.

In construction processes, equipment changes not only positions but sometimes postures. With angular and linear sensors, the postures of equipment could also be monitored, e.g. the movement of the arm of a tower crane (Y. Li & Liu, 2012; Rezazadeh Azar & McCabe, 2012). Proximity detection system has seen several trials in the Netherlands, but not widely employed. The major barrier is that the IoT system requires considerable initial costs for the tags, sensors, and equipment (Interview 5, 6).

4.2.5 Gesture monitoring

Workers' onsite gestures are monitored for two purposes. First, monitoring the workers' motion to identify the 'near-miss accidents'; second, it helps to alleviate the effect of Musculoskeletal Disorders (MSDs).

'Near-miss accident' refers to the hazard risks neglected in safety planning phase. They have not caused any destructive or harmful results but have potential to become an accident under slightly different conditions (Phimister, Oktem, Kleindorfer, & Kunreuther, 2003). It could be estimated that behind each major accident, there are numerous near-miss accidents (Aria, Yang, Ahn, & Vuran, 2014). Therefore, the identification of these omitted hazards helps to prevent future accidents in the construction industry (Cambraia, Saurin, & Formoso, 2010; Wu et al., 2010). Traditionally, the identification of potential hazards mainly depends on workers' self-reporting and related personnel's subjective judgment. This fact leads to the result that a significant amount of near-miss accidents are still unidentified, formulating unmanageable risks (Albert, Hallowell, & Kleiner, 2014; Bahn, 2013; Carter & Smith, 2006).

The term Musculoskeletal Disorders (MSDs) represents a group of painful chronic disorders that may be caused by repetitive work (Wang, Dai, & Ning, 2015). MSDs threaten workers' health and wellbeing, and at the same time, cause enormous costs for both the industry and the healthcare system (Alwasel, Elrayes, Abdel-Rahman, & Haas, 2013).

Wearable devices and Big data (IoT, BD)

A motion tracking system has been introduced to help to assist these tasks, by monitoring the onsite workers' motion. Safety hazards usually cause disruptions in the pattern of onsite workers' gesture. Therefore, motion analysis provides clues for identifying the near-miss hazards (Yang, Ahn, & Vuran, 2014). Similarly, analysis of workers' motion helps to evaluate the risk of MSDs (Alwasel, Elrayes, Abdel-Rahman, & Haas, 2013).

With wearable inertial measurement units (WIMU) attached to the tested onsite workers, their kinematic data is recorded and analyzed.

By comparing the recorded movement pattern with the database, the potential hazards and the risks of MSDs could be identified.

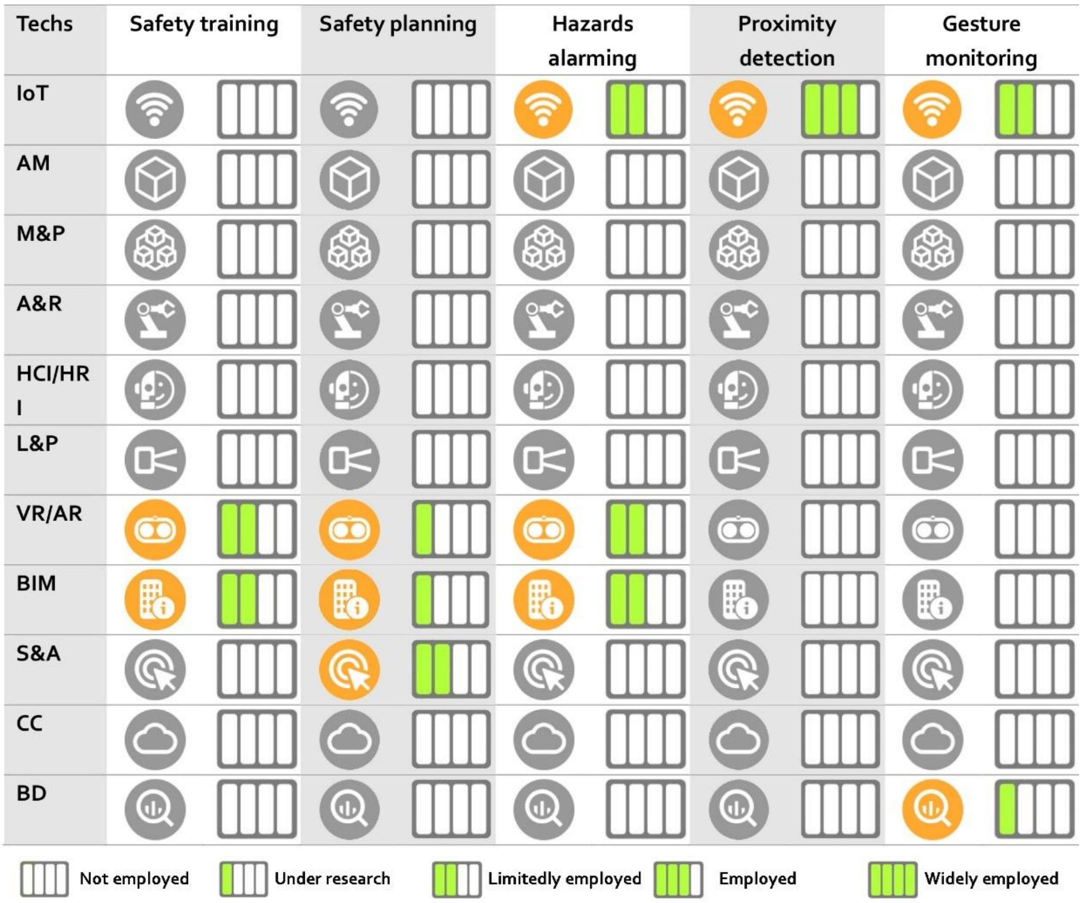
This system is new for the Dutch construction industry and has not been applied yet (Interview 5, 6). The employers are still using the traditional ways to deal with these works.

4.2.6 Summary

As a 'second type work', safety management is a relatively new field of construction robotics. No massive manual or repetitive works are involved in safety management, and its essence is the management of hazards information, including collecting information, processing information and sending the information efficiently to the related personals to avoid the hazards. Therefore, the mostly applied technologies in this field are not those belong to 'traditional' mechanical ones, but those related to information management.

Five of the elven identified clusters of technologies in Chapter 3 are employed in the construction safety management, including Internet of Things (Wireless Sensing, Wearable devices), Virtual Reality and Augmented Reality, BIM, Simulation and Algorithm (Virtual Prototyping), and Big Data (Figure 4.9).

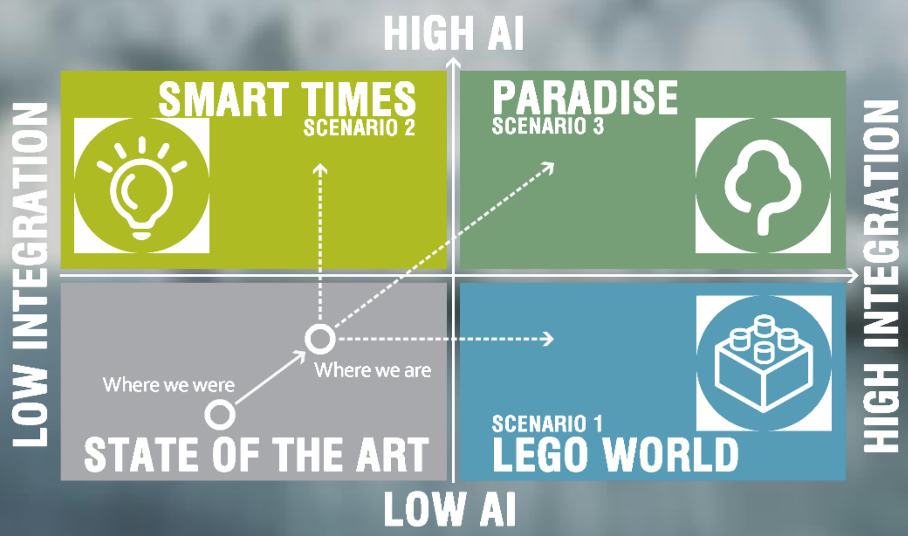
Figure 4.8. Technologies in construction assembly



5. Future study

Key Points

- Eight factors that may affect the direction of development of construction-robotic technologies in the future are identified: Labour Rights, Regional Growth, Artificial Intelligence, Additive Manufacturing, Energy Supply and Carbon Emission, Availability of Employees, Integration of the Construction Industry, and Monopolization.
- **Artificial Intelligence** and **Integration of the Construction Industry** has the highest impact and highest uncertainty, and therefore, are selected to establish the scenarios.
- With these two factors, a matrix is established, with the four quadrants representing state of the art, and three possible scenarios of the future.



- By analyzing the possible evolvements of the currently available technologies, the future landscape in construction assembly and safety management are depicted.
- The overlap of the three scenarios is the most solid fields for contractors to invest.

5.1 Preparation

5.1.1 Factors identification

As mentioned in Chapter 2, the possible future landscapes of the construction robotics will be explored in a set of scenarios. The scenario-planning bases on the factors that are relevant to the future evolvements of construction robotics technologies. By a series of expert interviews, eight major factors are identified. The details of the interviews can be found in Appendix C.

Labor rights

The original purpose of construction robotics is to replace human labors in the construction industry. However, in the history, applications of technical innovations have always been accompanied by the topic 'machines are taking jobs from human workers'. The social pressure generated by such protests may affect the demand of construction robotics. To compromise the pressure, contractors may prefer to adopt the technologies that do not reduce working positions (Interview 2). For instance, BIM helps to improve performance in construction by managing building information, without reducing any positions; meanwhile, some human-replacing technologies, e.g. single-task robots, are less likely to be adopted with the background. The shifts of the contractors' demand may apply an impact on the orientation of robotic technologies' in the future, from human-replacing to performance-improving.

Regional growth

Various demographic evolvements affect the demands on the local construction market differently. Growing population creates opportunities to construct new buildings; while in depressing regions, very rarely new buildings are constructed, with most of the construction activities concentrating in the fields of renovation, refurbishment, and maintenance. Robotic technologies required by the two types of construction practice are likely to evolve differently (interview 4).

Artificial intelligence

Artificial intelligence is a key technical factor that may affect the future of construction robotics. It is always mentioned that the unstructured onsite environments impede the application of automation and robotics technologies in construction (Kumar, Balasubramanian, & Raj, 2016). Robots work depending on the program embedded in them. However, in an unpredictable circumstance, the preprogram cannot work well. Therefore, human labors are still required to assist the process. With the development of techniques in machine learning and thinking, these problems may be solved. With the assistance of by artificial intelligence, robots and robotic systems could learn automatically, being able to handle more complicated tasks (Interview 3). Thus, AI may completely change the construction robotics technologies.

At the same time, this factor is also controversial. The application of AI in construction practice brings ethic discussions. As Professor van der Zee mentioned in the interview: 'Do we allow the AI to make mistakes? We all learn from mistakes, as well as AI; who will be responsible for its mistakes?' (Interview 2).

Additive manufacturing

Another more famous name of additive manufacturing is 3d printing (Interview 3). Although some pioneer projects have been implemented, large-scale application in practice has not been realized. The most significant contribution of additive manufacturing is that the construction processes are no longer subjected to the specific crafts or equipment, but to only digital inputs; thus, the producing costs of customized product will be more or less the same with standardized ones, and individualized buildings will be promoted.

Energy supply and carbon emission

Energy consumption is concerned for three reasons. First, to guarantee the sustainable development of human civilization; second, to suppress the global warming; finally, to reduce the impact of possible high energy cost in the future. Therefore, new technologies are trying to find a balance point between energy-consumption and performance-improving. New technologies enhancing working efficiency or performance slightly with too much extra energy consumption are considered unworthy. However, in the future, if alternative energies, e.g., solar and nuclear power, are applied on a large scale, this balance point may move to the performance-improving end.

*Availability of employees in the construction industry**

In a circumstance where employees are in shortage, innovations tend to go further to the automatic direction to save labor cost. Here the term 'employees' refers not only the manual workers, so-called 'blue collars', but also the 'white collars' if the technologies in the future are able to handle more intelligent works (Interview 4). The development of this factor is decided by multiple elements, for instance, the demographic evolvement, the immigration, economy pattern, as well as the attraction of the construction industry.

Integration and globalization of the construction industry

Compared with the manufacturing industry, the construction industry is highly fragmented. The manufacturing industries, for instance, car manufacturing, organize themselves and the whole supply chain very effectively because they work on standardized products; whereas in the construction industry, each project based on a unique assignment; after the project is finished, the contractor will move to the next one, with a different team from the previous one. Different assignments lead to unique products, while various teams lead to unique processes. With both product and team differ every time, the construction activities are highly fragmented. The experience accumulated in a project can hardly be employed in the next one. In recent years, some efforts of integration in the construction industry have been observed. For instance, some companies are beginning to provide full-prefabricated standard houses, including some international companies (e.g. IKEA and MUJI), as well as local ones[2], trying to integrate the products and producing processes, reduce the fragmentation of each project.

If this new business model becomes popular in the construction industry, it may drive the construction industry into a similar path with manufacturing industry, with many works moved from onsite environments to indoor circumstances. The robotics technologies will be greatly different.

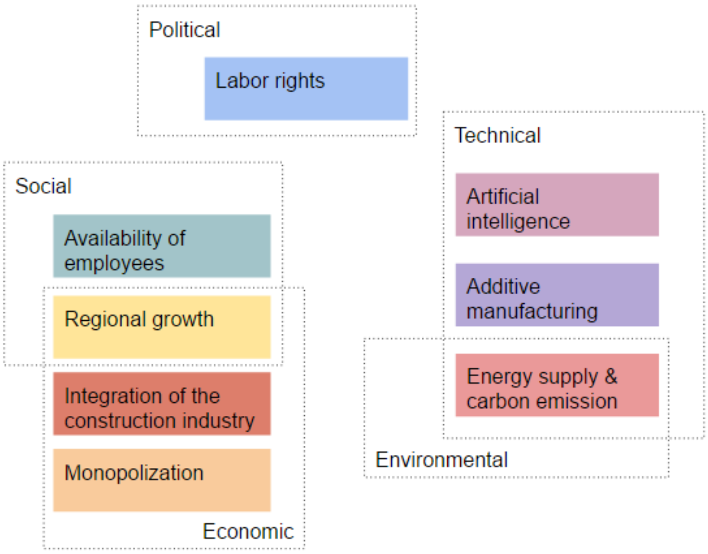
Monopolization

Some interviewees mentioned the fact that big companies and small companies have different patterns in construction robotics research and development (Interview 2, 4). The big companies can afford a higher research cost and initial investment than the small ones. Therefore, big companies are more likely to develop or adopt some expensive 'heavy technologies'. For instance, in the 1980s and 1990s, some leading top-scale construction companies in Japan developed the Construction

[2] For instance, the company GroothuisBouw. https://www.groothuisbouw.nl/

Factory System (see section 4.1.5) to enhance the automatic and robotic level of onsite construction. The system is costly and heavy, very rarely adopted by smaller contractors, who are more interested in the 'light and smart technologies'. Thus, the extent of monopolization of the construction market may affect the robotic technologies' evolvement in the future.

Figure 5.1. Categorization of the factors that affect the future development of construction robotics technologies



5.1.2 Factors assessment

As described in Chapter 2, the factors used for scenario planning should be highly uncertain and have high impacts on the development of construction robotics technologies. An online survey is conducted to assess these factors. For each factor, three questions focus respectively on its impact, predictability, and the possible development direction in the future. Each question could be answered using a 7 point Likert scale, as the example shows in box 5.1. The complete questionnaire can be found in Appendix D.

Box 5.1. Example of questions

Factor 1: Labor Rights

Introduction: (see section 5.1.1)

Question 1: To what extent do you think the labor rights movements impact the future development of construction robotics technologies? From 1 (No impact) to 7 (Extremely great impact).

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

Question 2: How predictable do you think the development of labor force movements is in the next decade in the Netherlands? From 1(Not predictable at all) to 7 (Highly predictable).

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

Question 3: How active do you think the development of labor right movements in the Netherlands will be in the next decade? From 1 (Not active at all) to 7 (Highly active), or 0 (difficult to say).

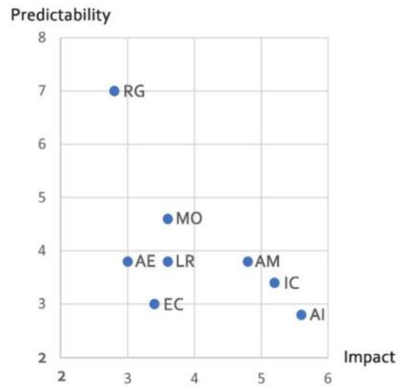
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 0 (Difficult to say)

The average scores of the first and second questions indicate the impact and predictability of the factors. The results are illustrated in Table 5.1 and Figure 5.2.

Table 5.1. The results of the assessments of the identified factors

	Impact	Predictability
Labor right (LR)	3.6	3.8
Artificial intelligence (AI)	5.6	2.8
Additive manufacturing (AM)	5	3.6
Energy supply & carbon emission (EC)	3.4	3
Availability of employees (AE)	3	3.8
Regional growth (RG)	2.8	7
Integration of Construction (IC)	5.2	3.4
Monopolization (MO)	3.6	4.6

Figure 5.2 Results of the assessment of the factors



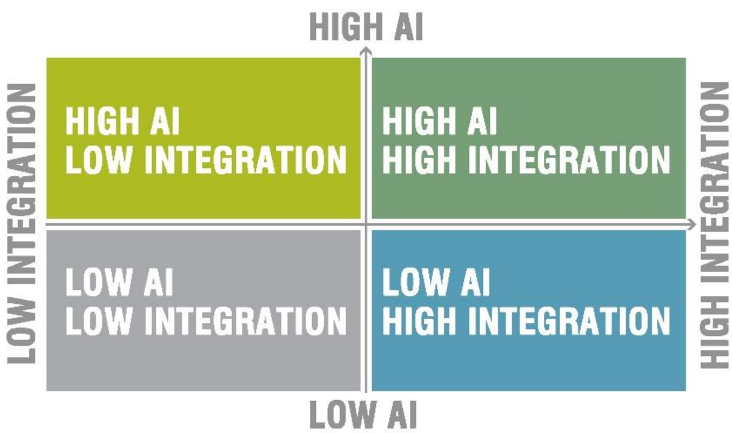
The two factors selected for scenario planning are Artificial Intelligence and Integration of the construction industry.

5.2 Scenario planning

5.2.1 Scenario matrix

With the combination of the two factors (development of Artificial intelligent and the Integration of the Construction Industry), a scenarios matrix is established (Figure 5.3).

Figure 5.3 Scenario matrix



Artificial intelligence

In the scenario planning, the factor *Artificial Intelligence* has two possible development direction: high development and low development. The definitions of high and low developments are related to the concept of strong AI.

A Strong AI is an AI that understands itself well enough to self-improve, which gives it the ability to learn. Even if it cannot perform all cognitive tasks as a human being does, this AI can still automatically execute optimization tasks or good decision-making. A Weak AI, in contrast, is an AI without or with limited ability to self-improve, which means it cannot teach itself and everything it executes depends on the embedded program. With powerful calculation capability, it may perform better than human in specific tasks, but it cannot take other tasks until it is 'taught' how to deal with them (Nilsson, 2014).

Nowadays, the weak AIs have been already applied in everyday life. For instance, by reviewing the historical search records, some websites are able to push related information to specific visitors to enhance the precision of advertisements. However, this process depends on the algorithm that embedded in servers, which is not able to evolve automatically, and therefore, the algorithm is still a weak AI. For the future, AI experts have entirely different expectations. The most optimistic ones believe that the strong AI will appear in the next decades, while some others claim that it is not possible to happen within fifty years (Müller & Bostrom, 2016).

In this research, the high AI development is defined as a vision in which strong AIs have been employed in the construction industry, taking over most of the work that currently executed by human workers, and therefore, the automatic level of the industry would have been largely enhanced. The in the world of low AI development, no remarkable breakthrough in the AI is achieved before 2030, and the automatic level in construction does not improve a lot compared with that in 2017.

Integration of the construction industry

In the scenario planning, the integration of the construction industry means that the suppliers adopt a producing method more like that in the manufacturing industry, providing standard on-hand models for clients, and organize the production chain within the control of themselves,
to limit the uniqueness of product and process of each project.

However, the construction industry is less likely to be integrated to the level in the manufacturing industry. First, the massive standard construction fits the simple and small buildings well, but not necessarily for the complex and iconic buildings. Second, the immovability of buildings attaches them to the sites, which are naturally different, meaning that the uniqueness of each project can never be completely diminished. Finally, people have been used to the current way in the construction industry, and their habits are difficult to be completely changed in short time (Interview 7). Thus, the integration level in construction may meet a ceiling.

In the scenario planning, high integration level refers to the futures that the actors in the construction industry construct buildings in a 'manufacturing industry way', standardizing the products and processes, especially for the small and simple buildings. Low integration in construction is defined as the situation more or less the same with the current situation; buildings are constructed in the 'construction industry way', which is more fragmented.

5.2.2 Where we are and where we were

By now (the year 2017), the construction industry is still at relatively low levels in AI and integration; however, looking backward, some progress has been made in both of the two dimensions.

In the past few years, the world has witnessed AI's expansion in the construction industry. For instance, Komatsu started Smart Construction in which UAVs (Unmanned Aerial Vehicle) is employed to survey construction sites, draw 3D maps, extract blueprints, and simulate construction plans. Now, processes such as these that can typically take weeks can be done in one day. Some companies are trying to apply AI in construction processes, by exploiting expert systems which include evidence of designs that have been done in the past several decades. These expert systems can intelligently provide suggested designs, assist in reviewing and verifying designs, and offer engineers a large amount of knowledge that would otherwise be unbeknownst to them. Also, AI in post-construction has been trending in the form of smart home systems and IoT (Internet of Things), e.g., Samsung

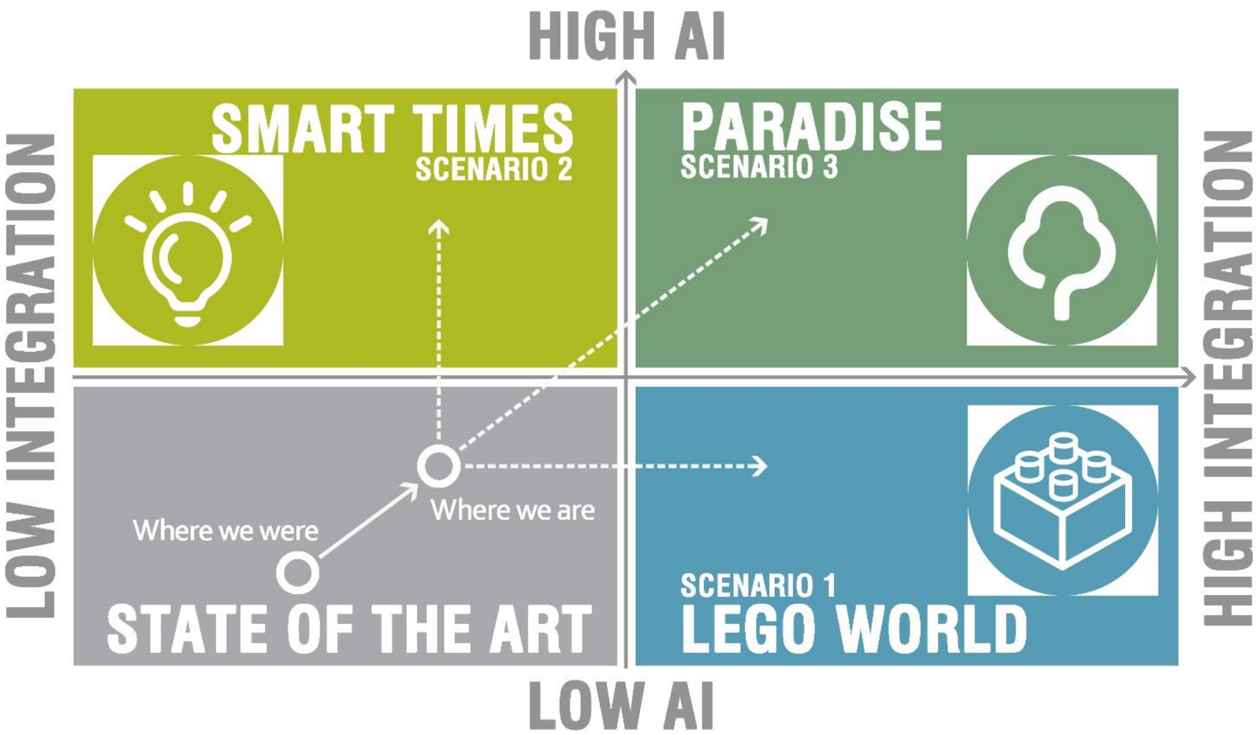
C&T is making efforts to the intelligent system that controls temperature, lights, electricity, locks, and robot vacuums according to users' voice commands or the changes of environment. Even the jobs in the design phase are being taken over by AI: the computational BIM product (GenMEP) proposed by BuildingSP, is an add-on to Autodesk Revit that uses computer algorithms to automatically route MEP systems through Revit models, with the goal of minimizing complexity and maximizing efficiency.

Efforts to integrate the construction industry could also be observed. Some suppliers in the construction industry are beginning to provide standard products from which the clients could select, and the provider will then deliver and erect the building. For instance, the famous Japan household products retailer, MUJI, launched standard home MUJI HUT, which is big enough for three to four persons (Figure 5.4). In the Netherlands, the company GroothuisBouw is doing the same thing. Some international companies, e.g. Google and Ikea, are also trying to expanding their business into this field.

Figure 5.4 MUJI HUT (Source: 'MUJI HUT', n.d.)

The previous and current positions, as well as the evolvement path, are illustrated in Figure 5.5. In the future, the construction industry may evolve along different paths, into three scenarios.

Figure 5.5. Scenario planning



5.2.3 Interactions between factors

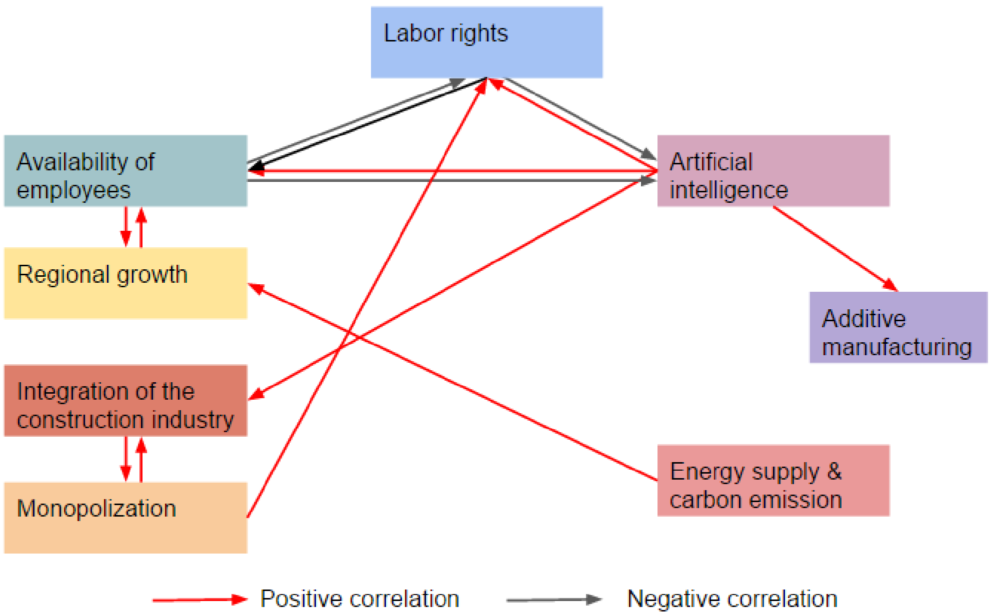
Eight major factors are identified in section 5.1.1, and two of them are employed to establish the scenarios. Therefore, in each of the three scenarios, the developments of these two factors are 'given', combined in different ways (scenario 1: high integration, low AI; scenario 2: low integration, high AI; scenario 3: high integration, high AI). As there are interactions between the eight factors, the different combination of the two most crucial factor will affect other factors. Therefore, it is necessary to discuss their evolvements in the three scenarios, making the scenarios more detailed.

Complicated interactions exist between the eight factors. For instance, the development of artificial intelligence takes over jobs from human labors and therefore, probably aggravating the labor right activities. In this research, the interaction between factors is classified into five categories: positive correlation (+), zero correlation (o), and negative correlation (-). These interactions are evaluated in Table 5.2 and illustrated in Figure 5.6.

Table 5.2. The interactions between the identified factors

	LR	AI	AM	EC	AE	RG	IC	MO
Labor right (LR)		+	o	o	-	o	o	+
Artificial intelligence (AI)	-		o	o	-	o	o	o
Additive manufacturing (AM)	o	+		o	o	o	o	o
Energy supply & carbon emission (EC)	o	o	o		o	o	o	o
Availability of employees (AE)	+	+	o	o		+	o	o
Reginal growth (RG)	o	o	o	+	+		o	o
Integration of Construction (IC)	o	+	o	o	o	o		+
Monopolization (MO)	o	o	o	o	o	o	+	

Figure 5.6. The interactions between the identified factors



5.2.4 Evolvement of other factors

Regional growth

The essence of regional growth is demographic development, which is highly predictable (Qin et al., 2014), and it is hardly impacted by the two key factors (AI and IC) in scenario planning. Therefore, in the three scenarios, it will evolve in similar paths.

In the Netherlands, by the year 2030, the population will reach around 18 million (CBS, 2015). However, the increase will mainly happen in the Randstad area, while in the periphery of the country, population growth will be slower, some municipalities will even face a decrease (Euro Monitor International, 2015). According to the precast of CBS (2011), the population in the Randstad area will grow 700,000 between 2015 and 2025. Therefore, it could be expected that in the major metropolitan of the Netherlands, the construction industry will keep active in the next decades, to accommodate the newly increased population. At the same time, the Randstad area has a large amount of old stock, and its prosperity will also drive the demand for renovation and refurbishment projects, as well as the demand for new buildings.

Monopolization

Integration of the construction industry promotes the monopolization level. It promotes the standardization of buildings, introducing massive production into the construction industry. Thus, the big companies enjoy scale economy, taking an advantage in the competition, and are likely to purchase the small ones gradually. Finally, a few large suppliers remain.

On the other hand, highly developed AI promotes the automatic level of construction processes, enabling small contractors to do more works, thereby strengthening their positions in competition, keeping the construction market at a relatively low monopolized level. Therefore, in scenario 1, the monopolization level will increase; in scenario 2, the monopolization of market remains at a low level; in scenario 3, the market will be somewhere between the previous two scenarios.

Availability of Employees (employee shortage)

Now (2017), the labor supply in the Dutch construction industry is slightly tight (interview 5). Although the Randstad area is going through a continuous booming with a growing population, craftsmen are still in shortage. Blue collar is not an ideal position for most of the young people, and the average age of building workers are increasing. Now in the Dutch construction industry, labors from eastern European countries (e.g. Poland) help to ease the shortage; however, due to the increase of income in the eastern Europe, the labors from these countries are disappearing (Interviews 4).

In scenario 1, integration of the industry enables a large part of the building activities to be finished in plants and factories, which is expected to reduce the labor demand. However, taking into account the fact that the prefabrication level in the Netherlands had already reached a quite high level (Pribaz & Fine, 1994), the release will be limited, and the shortage is more likely to continue.

In scenario 2 and 3, highly developed AIs take over most of the jobs, including most of the manual works, organizing and planning works, even part of the design works. The employees needed in the construction industry will be greatly reduced, and the shortage of labor force will not be a big problem anymore. At the same time, the construction industry will need some ICT experts to manage AIs and related issues.

Labour rights

Labor rights activities are related to the fact that human workers' jobs are being replaced by machines, robots, and AIs. The job losing stimulates the labor-right activities, applying pressure on the further development of the technologies. However, at the same time, the historical experience indicates that new jobs will always be created, providing new positions. Most people have realized that the technical progress would benefit, and the governments always encourage the technical innovations. Besides, the sound social security system in the Netherlands alleviate the contemporary conflicts. Therefore, the labor rights activities are less likely to boom the future years in any of the three scenarios.

Additive manufacturing

Currently (2017), additive manufacturing has not been applied in the general onsite construction practice. The most significant obstacle to its wide application is the scale of the 3D printer. The scale of products of the 3D printers is limited to a few meters in all the three dimensions; while most of the buildings in daily life exceed the scale. The most promising solution to this problem is the swarm printing, which employs a set of printing robots moving on the construction site, cooperating with other printers to finish the work. Another two alternative solutions include building larger printers[3], which suffers low speed and low accuracy; and printing the whole buildings to a series sections and assembling them on-site, which requires more onsite works, increasing the building costs.

In scenario 1, additive manufacturing may develop to the direction of printing large components in sections. Currently, 3D printing has already been employed in prefabrication of building components, mainly the relatively simple components such as pillars, wall panels, or slabs. It is expected that in a few years, printing components of complicated shapes will be feasible in practice.

In scenarios 2 and 3, all the three solutions may get some progress. With the support of AI, it is possible to manage complicated swarm cooperation between individual printing robots; also, a single printer cannot print components with various materials, while multiple printers help to solve the problem. Therefore, 3D printing in these two scenarios is more likely to evolve into the direction of swarm printing.

Energy supply and consumption

The energy supply and consumption is a relatively independent factor, being less affected by other seven factors. Compared with other European countries, the Netherlands lags behind in energy transition, with less than 10% alternative energy in the total energy supply (R&Dialogue, 2015). It could be expected that in the following decade, the energy supply in the Netherlands will continue to depend on the traditional energy (fossil fuel). Therefore, in the recent future, energy saving will continue to be a major consideration in the technical innovations, and this does not differ a lot in the three scenarios.

Table 5.3 The evolvements of the factors in the three scenarios

<table>
<tr><th>Factor</th><th>Scenario 1</th><th>Scenario 3</th><th>Scenario 2</th></tr>
<tr><td>AI</td><td>Low development
Stay in the Weak AI phase; AI can only assist to do simple works;</td><td colspan="2">High development
Strong AIs have been realized and widely employed in the construction industry;</td></tr>
<tr><td>IG</td><td colspan="2">High development
A few global suppliers take a remarkable share of the market; brands become more important in the construction industry, as in many other industries.</td><td>Low development
Similar to the current situation, many contractors active on the market.</td></tr>
<tr><td>AM</td><td>Low development
Evolve along the present path, mainly depending on printing buildings in section and assembling them on site.</td><td colspan="2">High development
With the assistance of AI, the application of additive manufacturing may achieve breakthroughs in all the three possible solutions.</td></tr>
<tr><td>MO</td><td>High development
A few global tycoons take a remarkable share of the market.</td><td>Medium development
Some global suppliers play important roles, while the small and localized companies are more active in other buildings.</td><td>Low development
Small and localized companies remain the main body of the market competition.</td></tr>
</table>

[3] See the website: http://d-shape.com/

LR	Low development Labor rights activities are less likely to be very active in foreseeable time horizon.	
EC	Low development By 2030, it is most likely that the fossil fuel will continue to be the most important pillar in the energy supply, and the tight balance will continue;	
AE	Relieved Massive production reduces the labor workers needed in the construction industry;	Highly relieved Strong AIs take over most of the positions in the construction industry, much fewer employees needed;
RG	High development According to CBS, the Randstad area will keep a robust growth in the next decade, increasing 700,000 new residents between 2015 and 2025. The development will increase the demands for both of new development and renovation in this metropolitan area.	

5.3 Scenario Narratives

The three scenarios share some similar backgrounds, including the regional growth, energy supply, and political labor rights activities.

The Randstad area keeps continuously prosperous. The active economy and growing population create robust demands for different types of buildings, including housing, offices, schools, hospitals, hotels, leisure buildings, warehouses, and industrial facilities. New urban blocks are developed in rural areas, transiting them into built environments; at the same time, some residents, especially the young ones, prefer to live near the city centers. Therefore, the old stocks located in traditional town zones continue to stay in service, generating considerable demands for renovation and maintenance.

No big leap has been achieved on alternative energy. Neither solar nor wind power can replace fossil fuel's dominating position. Fission power is being criticized by environmental protection organization, bearing great political pressure, and losing its share in energy consumption to other energy sectors. No possibility can be seen in the commercial use of fusion power; carbon emission and energy shortage still threaten the future of human civilization. Therefore, energy-saving is still an important orientation in technical innovation.

Political activities against technical progress are rarely heard, although more and more jobs which are done by human workers are taken over by newly developed technologies, for instance, self-driving vehicles. With the technical progress, more new jobs have been created, compensating the lost positions.

The distinctive features of the different scenarios are described in the following narratives.

5.3.1 Scenario 1: LEGO WORLD

The fourth quadrant represents scenario 1, which is characterized by the following features:

- Products integration: brandization and standardization of residential buildings;
- Market and process integration: fewer, bigger, and more versatile players;
- Globally-distributed massive production in the construction industry;
- Higher modularisation and prefabrication in construction;
- Human workers are still dominating the onsite works, and labor supply will be slightly tight.

Products integration: Brandization and standardization of residential buildings

Compared the fragmented producing way in the construction industry ten years ago, today, the massive construction has already been popular. It is more like the working method in manufacturing industries, in which the suppliers organize the producing processes based on standard products.

The trend was initiated by some actors out of the construction sector in the early 2010s. MUJI started its 'housing order' service at the beginning of the 21st century, selling standard off-grid houses – which are more like campers, taking advantages its resources and experience in global supply chain management in furnishing field. In 2012 IKEA joined, launching totally-prefabricated affordable houses to the market, actually starting a new business mode. These products are standardized, and the clients only need to do place an order online. Once the order is confirmed, the components will be produced in plants and then transported to the site to erect the building.

For the clients, this new way brings at least four benefits. First, they choose the products that best fit their demands to be built, instead of choosing one to buy from the already-built ones, reducing the difficulties of purchasing a property. Second, the reputation of suppliers provides a guarantee for the buildings; the clients could spend less effort on examining the quality. Third, all of the components are prefabricated in building plants, where the working conditions are more stable than on site, the building quality is less affected by environment. Finally, the prefabrication in construction reduces the cost of the buildings, making them more affordable.

Thus, in the second half of the 2010s, this more integrated method in housing market became popular. As a result, brands became important, as in other industries. The first characteristic of buildings has changed from the 'owner' of the 'brand'. In the old times, when people see a big, fabulous house, they probably will ask, whose house it is? However, now, the first question that most people concern is likely to be, what is the brand of the house? Houses have already been taken as common commodities as cell phones and cars, spotlighting their logos. Walking on the street, especially in the newly developed area, it feels like a supermarket of houses. Not surprisingly, most of these products are standardized models to reduce the producing cost, and the similar models often share the same components. All these have enhanced the integration level of products in the construction industry.

In the beginning, this new method is employed only in the detached houses. When this new business model came to Europe and Asia, where detached houses are less common, it expanded into the collective housing field. The housing suppliers established their developing departments, collecting residential demands in certain areas, providing multiple layouts for the potential clients to select. Interested buyers could order a flat in their projects. Then the design will be made according to the clients' demands, and the ordered units will be prefabricated in factories and sent to the construction site to be assembled. They work in a similar way to housing coalitions. The Dutch government and housing associations have also joined in, cooperating with the housing suppliers to construct the affordable collective residential buildings.

With great advantages in cost and building period, this new business model soon occupied a considerable share of residential building market and is still growing.

Market and process integration: Fewer, bigger and more versatile players, but small companies still on board

The integration of products led to the integration of market in the residential building fields. With the advantage of economy scale, the big companies are more competitive than the smaller ones. At the same time, they take another advantage in producing period. The small companies usually begin to produce the building components after their clients submit their orders, while the big ones can produce those in advance according to the big data of their sales, thus greatly shorten the time that the customers have to wait. This further strengthens their competitiveness. In the competition, the big companies are more likely to survive.

In the other fields of the construction industry, players intend to integrate the construction process by purchasing subcontractors, and companies from upstream (e.g. initiate, design, and finance) and downstream (e.g. operate and maintenance) industries, to cover the whole lifecycle of buildings. Thus, they integrate the process by controlling a longer part of the chain, and the waste in works' handing over is reduced.

Small companies still exist. The standardization level is limited, because of people's pursuits for personalities. Although the standardized buildings are faster and cheaper to build, there is a balance point between these benefits and the loss of personality. Even for cars, which are highly standardized, the owners often need some personal decoration to show their personalities. So, some clients choose the semi-finished products and finish the final touch themselves, for instance, painting, interior finishing, etc., to make their buildings special. These demands provide space for small companies.

Globally distributed massive production

The trend of standardization and prefabrication enables the massive production to be introduced into the construction industry. Standard building components are produced on streamline in factories. Similar to many other industries, the manufacturing departments are distributed all over the world to reduce the costs. The components are transported to the construction site. through the global logistic system.

Higher prefabrication level in construction

Inspired by the totally-standardized producing method of residential buildings, the construction out of this sector has also reached a higher prefabrication level than ten years ago. As mentioned previously, some traditional big contractors have joined the market of 'standardized houses', establishing their production systems. They try to take advantage of these systems to facilitate their business in 'traditional constructions'. As some of them have integrated the design phase into their business, a design-and-construction-system similar to LEGO has been developed. The buildings are designed in such a way that they could use standard components as much as possible. Thus, the production system for standard residential buildings could be employed to contribute the construction in non-residential sectors. A considerable part of buildings is built with standard components, which could be produced by the plants in the producing systems.

Human worker dominated onsite works

The onsite works, however, has not changed a lot since the 2010s. Human workers dominate the process, with the assistance of the robots. Some progress has been achieved to miniaturization of robots. Therefore, they are employed more than in the 2010s, but still, they need to be guided by human workers. With the process of economic homogeneity of the EU countries, cheaper labors from the eastern Europe are disappearing[4]. As a result, the construction industry still needs to face the problem of labor shortage. Therefore, technical innovations aiming at saving labors are still encouraged.

5.3.2 Scenario 2: SMART TIMES

The second quadrant represents scenario 2, which is characterized by the following features.

- AI-supported highly automatic onsite construction process;
- Wide application of robots and the reduced demands for labors;
- Information technologies dominate the construction;
- Many small companies survive, and are active on the market;

[4] In the interview, Professor van Gassel said that currently, the Dutch construction industry to a considerable extent relies on the manual labors from Eastern European countries, e.g. Poland.

- Construction robotics is applied in maintenance and renovation projects of existing stocks.

AI-supported highly automatic onsite construction process

Artificial intelligence has gone through an intense development in the last decades. In 2022, the first strong artificial intelligence appeared, being able to with learn and think automatically. Since then, the AI technologies boomed, and the prices of AI had been reduced quickly. Within three years, personal AI became affordable to ordinary people, and the industrial AI began to be employed in companies to control production activities.

As a result, construction activities have been highly automatic right now. In automation of onsite construction processes, the obstacles came from not the mechanical aspects, but the cognitive aspect. Professor van Gassel gave an example of picking tomatoes in the interview. Employing robots to execute the action 'picking' is easy to realize, while the difficult part is how to enable the robots or machines to decide whether a tomato is ripe enough to be picked. In the past, this mainly depended on human's judgment; now, AIs can learn from a database of related experience, even search solutions online automatically, and then control the robots to conduct the tasks.

At the same time, AIs could take over the process organization, reducing the involved actors and the uncertainties they bring, making the process more impact, reliable, and manageable. In the interview, Michel Bottema gave an example (Interview 8). In the Netherlands, the building activities suffer from wind weather, because it makes the cranes unstable. With a self-learning AI managing the schedule, it could look up weather forecast online and according to which, adjust the construction schedule, informing the stock managing robots to prepare the materials and equipment that will be used for the day, and send them to the construction site. These works could be done by human workers, however, with delay and inaccuracy; if AI takes over, the process will be much more compact.

Wide application of robots and the reduced demands for labors

With the assistance and control of AIs, robots' application greatly has boomed, taking over most of the onsite works. For instance, AIs control the excavators to handle the earthworks, moving according to the pre-planned process. At the same time, the work process is monitored by multiple unmanned aerial vehicles, which transmits the image to the controlling AI in real time, and the AI compares the real-time image and the design model, adjusting the next move of the excavator. Similarly, moving materials, pouring concrete, welding and bolting the steel structures, are also executed automatically. Except for the single robots, swarm robots are employed due to the development of natural network theory. A swarm consists of multiple individual robots, which are smaller and much more flexible, being able to execute small tasks individually or cooperate with each other on complicated tasks. For instance, on-site 3D printing has been realized by the cooperation between a group of smaller printing robots, each of which is tiny.

Not only the manual works but also in some 'intelligent works', for example, the organization and management of the construction, AI has partly replaced human workers. Even in the design phase, some simple and small buildings could already be designed by AI. Thus, employees in the construction industry have been greatly reduced, to a level that no one can imagine twenty years ago. The prices of construction have been lowered because of the much less demand of human labors.

Information technologies predominate the construction industry

In the AI-and-robot-assisted construction process spotlights the importance of information technologies. In construction processes, AIs stand at the central place, controlling the whole process; it needs information and resources to support its decision-making, including the site condition collected by sensors, rules for judgments, and solution database (interview). If necessary, it could connect to the web and find proper resources online. Thus, information support is the most important sector in AI dominated construction process. Some organization provides related resources. For instance, a repayable cloud database that supports AI's control on construction sites. The controlling AI could search and learn solutions for specific problems it met in building processes.

More small companies on the market

The development of AI has strengthened the competitiveness of small companies, enabling them to do more work than previously. For instance, in the 2010s, most of the contractors on the Dutch construction market has only one or two employees, which mainly undertake repair works and simple maintenance works in the neighborhood (interview). Right now, however, with the help of AI and robots, each person could supervise one small project, such as a detached house.

Highly developed AIs also reduce the motivations of the contractors to purchase upstream and downstream companies. With specific process managing AIs, the complicated handing over between different actors now could be effectively managed, with each actor in projects being aware of what they need to provide and what they can get from other actors. Great optimization and integration of the process have been realized, and the companies are less motivated to purchase other companies to reduce the uncertainties.

Construction Robotics is applied in maintenance and renovation projects of existing stocks

AIs help the construction robotics to become more flexible, being able to adapt more complex working environments. Thus, the construction-robotic technologies could be employed in more construction tasks, including the maintenance, renovation, interior finishing, etc., which were dominated by manual methods previously. This has brought significant benefits to the Dutch construction industry because the historical stocks take a considerable part of the construction activities in the Netherlands.

5.3.3 Scenario 3: PARADISE

The first quadrant represents scenario 3, which is characterized by the following features.

- Highly automatic building process and massive prefabrication;
- Customization as a popular business model;
- Medium monopolization;
- Localized production.

Highly automatic building process and massive production in construction

Similar to Scenario 2, highly-developed AIs automatize the building construction processes. Most of the human labors have been replaced by the AI-controlled robots. At the same time, similar to scenario 1, the construction industry is highly integrated, with the massive production popular in residential buildings.

AI-assisted customization

With massive production combined with highly automatic building processes, online customization has been a popular service in the construction industry. Customization is the traditional working way in this industry: each building is designed by architects according to clients' requirements and then built. In the housing industry, most of the 'ordinary clients' can only choose from the ready-made products provided by developers. Now, thanks to the wide application of AI, and the massive production system, everyone can enjoy customization services.

House suppliers provide online platforms through which clients could talk with AIs, describing the requirements, according to which the AI will propose a layout. These layouts are made by making some adjustments to the basic models from the database. Therefore they are not as diverse as the human architects' works, but they are much cheaper and can fulfill the requirements of clients. After the layout is confirmed, the clients could choose a style, and then the AI will generate the design according to clients' selection[5]. As the designs evolve from several prototypes, they could be highly standardized, with most of the components could be massive produced. The AI assistance of the company summarizes the data dynamically to figure out the pattern of the demands of the market and adjust the production schedule.

For the larger and more complicated buildings, AIs are also able to involve. However, the design phase requires more powerful AI, which cost more money and time. Thus, the AI-customization is mainly employed in the residential sector. For other buildings,

Localized distribution of the massive producing system

Traditionally, the massive production mode tends to locate the producing systems in densely populated developing countries to reduce the labor cost. Now, with AIs employed, the labor cost is not a major contributor to the total cost any more. The distribution of the 'building factories' are affected more by the demand and market, transport cost, infrastructure status (transport system, power supply, etc.), as well as the tax and tariff policies. Most likely, they will be distributed near the market. The localization could be expected in this scenario.

5.4 Evolvement of current technologies in the three scenarios

5.4.1 Construction assembly

Internet of Things (IoT)

Currently, IoT technologies in construction assembly are employed to identify the components or materials to manage the onsite inventory and track their location in the conveying process. The available technologies include RFID (Radio Frequency Identification), GPS (Global Positioning System), and UWB (Ultra-Wide Band).

The driver of the application of IoT is the demand for recognizing and tracking the objects on site in construction practice. It has already been occasionally applied in the Netherlands. The main barrier comes from the practitioners' conservativeness (Interview 5), and the potential limitation of privacy-related law (Interview 6). In the future, with the increase in the use of IoT, the benefits it brings will be known more widely, and the conservativeness is likely to fade.

In Scenario 1, IoT will be widely used in construction assembly. High prefabrication level increases the types of components on site, requiring a way to manage the onsite inventory efficiently. In Scenario 2, IoT will also play a major role. AIs are employed to handle the construction activities, controlling robots to execute on-site works. Thus, a method is needed for them to identify and locate the objects. IoT could help to do that. In Scenario 3, both of the drivers in the previous two scenarios contribute. Therefore, the application of IoT will also rise.

Currently, specific readers are needed to detect the tags or chips attached to the objects, which causes inconvenience; in the future, a reader-free system, in which all the tags or terminals could report their locations to the central controller in real time, is desired (Interview 6).

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[5] According to the interview to Professor van der Zee, TBI has tried a similar project named 'Architects' DNA', which employ specific algorithm to generate a design that looks like a specific architect's work.

In the future, IoT can be employed to track the assembly processes. The tags attached to building materials and components report their location to the controller in real time; by reviewing their position, the operators are aware of whether they have been assembled in place.

The probable evolvements of wireless sensing technologies in different scenarios are summarized in Table F.1 (Appendix F).

BIM

BIM has been employed in the construction industry, especially in design phases. However, despite the potential benefits, BIM has not been widely applied to assist construction assembly work yet, although some studies have already revealed the possibility. The main barriers come from the lack of imagination to 'discover' new application, sometimes combined with other technologies (Interview 6). For instance, using BIM to get the final location of a specific building component and use the data to calculate the best conveying path is a creative application of BIM, improving the efficiency of on-site work. More new implementations are waiting to be 'dug out'.

In all of the three scenarios, a more fluid information flow in construction-assembly works is appreciated, which is the fundamental driver for BIM's application (Interview 6). With its wide application, BIM's contribution to assembly work will be realized by practitioners. Therefore, it is reasonable to believe that in all the three scenarios, BIM will be employed more in construction-assembly works. Especially in Scenario 2 and 3, where the controlling AIs need a digital database of the project's information.

There is not a complete and list of the items that BIM could be employed to do. More efforts should be invested in exploring more creative uses of BIM (interview 6). The probable evolvements of BIM in different scenarios are summarized in Table F.2 (Appendix F).

Handling robots/robotic systems (Automation and Robot, A&R)

Handling robots and robotic systems are mainly applied in the conveying phase, which currently consumes most labors in construction-assembly works (Feng et al., 2014), especially within the indoor environment, where cranes cannot reach. Labors protection also drives the demand for adoption of robots (Interview 6). For instance, in the Netherlands, an individual worker is forbidden from handling the weight over 20kg.

The current application of handling robots in the Netherlands are impeded by the fact that most of the robots are not swift enough to be used within an enclosed space (interview 6). The good news is, now, efforts are being made to miniaturize the handling robots to make it more flexible, and the interviewees are optimistic about the progress (interview 5, 6).

In Scenario 1, driven by the tight labor supply, the use of handling robots probably rise; they may evolve to the direction of miniaturization, and be more interactive with human labors so that they can work together. In Scenario 2 and 3, swarm robots may be preferable in Scenario 2 and 3. Swarm robots are standard and multiple-functional, and they are much easier and cheaper to maintain compared with a group of different types of robots. In these two scenarios, they may replace handling robots. Swarm robots can work individually to handle small objects, and they can work together to deal with big ones. Controlled by AIs, robots will be more intelligent, being able to self-adapt to the dynamic working conditions.

The probable evolvements of handling robots/robotic systems in different scenarios are summarized in Table F.3 (Appendix F).

Human-robot interaction (HRI)

HRI technologies now in the construction assembly are mainly employed to assist the cooperation between human workers and robots to integrate the advantages of both. For instance, a human worker and a robot could hold a component together, the strength that the human worker exert on the components could be perceived by a sensor embedded in robots, and the robots will cooperate with the human worker by exerting strength in the same angle and direction. Thus, the human worker could handle the components with more easily, and keep the flexibility. In the Netherlands, the application of HRI technologies in practice is limited, mainly because of the limited use of robots (Interview 6).

In scenario 1, as has been discussed in the last section, handling robots will be applied on a large scale, probably in cooperation with human workers. This landscape will drive the demand for HRI technologies. In Scenario 2 and 3, with AIs involved, human workers may quit most of the on-site construction activities, and therefore, the HRI technologies are very likely to decrease in the construction industry.

The probable evolvements of Human-robot-interaction in different scenarios are summarized in Table F.4 (Appendix F).

Laser Scanning and Photogrammetry (L&P)

Laser scanning could be employed to rebuild physical environments digitally. In assembly works, it assists to inspect the finished assembly work by comparing the built environment with the designed spatial model. This new inspecting method shortens the time needed and promote the precision of inspecting process. It has been used in the Dutch construction industry. In the past, the major barrier of laser scanning is the cost for devices; in the last few years, however, the price of an individual scanner has decreased to 30,000 to 40,000 euros, which is affordable to most of the contractors. Therefore, as a fast inspecting method, in all the three scenarios, laser scanning is likely to be widely used in inspecting phase (Interview 6).

Photogrammetry is an alternative of laser scanning, using pictures from different perspectives to rebuild digital model of the built environment. Compared with laser scanning, photogrammetry does not need to move slowly, which enables it to be attached to drones. Therefore, it could move automatically around the construction site to monitor the assembly process (interview 5).

The probable evolvements of Laser scanning and photogrammetry in different scenarios are summarized in Table F.5 (Appendix F).

Single-task robots (Automation and Robot, A&R)

Single-tasks robots are the first generation of robotic technologies, appearing in the 1980s (Bock & Linner, 2016). They are used to replace human workers in some repetitive works. However, their applications are scarce in the Netherlands for now.

The application of single-task robots onsite is limited by the unstructured working environments. For instance, bolting robots could stand by a stream to finish bolting work for each product; however, the onsite environments are more dynamic, and requires the robots to move to complete its work.

In Scenario 1, the application of onsite single-task robots is probably to increase slightly. The application of Human-Robot-Interaction technologies helps the single tasks robots adapt to the onsite environment better.

In Scenarios 2 and 3, similar to the handling robots, single-task robots will probably be replaced by swarm robots in construction practice. With AIs' support, robots are able to adapt to the working conditions automatically, without human labors' intervention, working in more complicated and dynamic environments.

The probable evolvements of Single task robots in different scenarios are summarized in Table F.6 (Appendix F).

Augmented reality (VR/AR)

Augmented reality is used to visualize the digital information to the human workers with particular devices (e.g. AR glasses and helmets) so that they could see the information intuitively without checking 2D drawings. Thus the workflows are made more fluid, and the construction periods shortened.

This technology was proposed as early as in the 1990s but was not widely used immediately, due to of the high initial costs of the AR devices. Since 2010, the cost has decreased, and the Dutch construction industry has seen some pilot projects applying AR. However, AR is still not widely applied because the AR devices are still expensive right now; besides, most of them are quite fragile (interview 5, 6).

Similar to the HRI technologies, the augmented reality's application is related to human's involvements in the construction process. In Scenario 1, human interactions remain necessary in construction; therefore, AR will be employed to enhance human workers' awareness of the related information. For instance, AR devices indicate the position of an object so that it could be identified and fetched by workers much more quickly. Meanwhile, in Scenario 2 and 3, augmented reality may be not widely employed due to the decrease of human labors in construction.

In the future, AR could be used in inspection. By visually imposing the designed model on the real environment, it enables the inspector to tell the difference of between the designed and built environments. Thus the possible flaws in construction could be distinguished easily. This application of AR can be employed in all the three scenarios. Although the construction processes are in highly automated in Scenario 2 and 3, the inspection phase will still depend on human workers, at least partially. It is less likely that in the recent future AIs are endowed the legal status to be responsible for its work (Interview 2).

The probable evolvements of Augmented reality in different scenarios are summarized in Table F.7 (Appendix F).

Construction Factory (Automation and Robots, A&R)

Although not very often, Construction Factory has been employed in the Dutch construction practice for a few times. For instance, in the project Rotterdam Medical Center (Interview 5, 6). Two barriers lie in its way to being widely adopted in the Netherlands. First, the CF equipment is heavy and expensive; second, the demands for high rise buildings are limited in the Netherlands and is less likely to change a lot in the next decade (Interview 6). Some lighter CF systems are being developed, which can be employed in the low-rise buildings (Chu et al., 2013), and so far, remarkable progress has achieved.

In Scenario 1 and 3, the construction factories are likely to be developed to some extent. The highly-integrated construction industry generates more big companies on the construction market, who are more able to afford the expensive, heavy equipment. Also, the high integration level leads to the increase of standardized buildings, which are proper to apply CF. At the same time, differences exist between the two scenarios. In scenario 1, the CF technologies remain more or less the same with what it is now; while in Scenario 3, due to the involvement of AIs and IoT, CF will evolve into a smarter and more integrated system. In Scenario 2, without new drivers and barriers appearing, the application of CF is likely to remain the current situation.

The probable evolvements of Construction Factory in different scenarios are summarized in Table F.8 (Appendix F).

Bottom-up system (Automation and Robots, A&R)

The system proper for all the three scenarios, and is likely to be widely used if it is financially feasible. By the year 2030, in all the three scenarios, renovation of historic urban areas is likely to remain as an important part of the Dutch construction industry (Section 5.2.1). Many construction sites locate in densely resided zones, and this fact generates significant demands for bottom-up systems.

The probable evolvements of the Bottom-up system in different scenarios are summarized in Table F.9 (Appendix F).

Summary

According to the previous analysis, the three scenarios of future robotic technologies in construction assembly is summarized in the following table.

Table 5.4 The scenarios of future landscape of the technical innovations in construction assembly

<table>
<tr><th></th><th>Scenario 1
LEGO WORLD</th><th>Scenario 3
PARADISE</th><th>Scenario 2
SMART TIMES</th></tr>
<tr><td>Internet of Things (IoT)</td><td colspan="3">IoT is widely used to manage inventory and track objects, making the workflow of construction assembly fluid. Reader-less systems have been realized, in which no hand-hold readers are needed to detect the sensors, and the sensors report their location to the controller in real time. IoT could also be used to monitor the assembly process.</td></tr>
<tr><td>BIM</td><td colspan="3">BIM is employed to assist the construction assembly. For instance, it provides the final position of a component to calculate the best path or designed models to be compared with the scanning models to check whether the work has been done as designed. More creative applications need to be figured out in the explored.</td></tr>
<tr><td rowspan="3">Handling robots/robotic systems (A&R)</td><td colspan="3">Robots and handling robotic systems (see section 4.1.2) are more employed in all the three scenarios but have evolved into different directions.</td></tr>
<tr><td colspan="2">The handling systems become larger because of the higher modularization level of the construction industry.</td><td></td></tr>
<tr><td>Robots/Robotic systems are more interactive with human workers to work together.</td><td colspan="2">Robots/Robotic systems are more intelligent, working without human intervention. Swarm robots may replace the robots which are specifically designed for handling.</td></tr>
<tr><td>Human-Robots Interaction (HRI)</td><td>HRI technologies are more employed to assist the cooperation between human and robots, because of the wide use of handling robots and single-task robots.</td><td colspan="2">HRI technologies decrease because of the less human involvement in onsite construction-assembly works.</td></tr>
<tr><td>Laser Scanning and Photogrammetry (L&P)</td><td colspan="3">Laser scanning is taken as a step in the standard inspection process, to generate a digital as-built model to compare with the designed model, helping inspectors to make quick judgments.
Photogrammetry is employed to monitor the assembly process, combined with drones.</td></tr>
<tr><td>Single-task Robots (A&R)</td><td>Single-task robots get developed to some extent. They are more miniaturized and interactive compared with the robots in the 2010s.</td><td colspan="2">Robots' application has been greatly developed. Swarm robots may replace the single-task robots. They are not designed for specific tasks, but multi-functional. They are much more flexible than single-task robots and cheaper to maintain.</td></tr>
<tr><td>Augmented reality (VR/AR)</td><td>Augmented reality is widely used to identify the target components from inventory stockyard; they are also used to provide visual guidance for human workers when they are conducting assembly works.</td><td colspan="2">Augmented reality decreases because of the less human involvement in onsite construction-assembly works.</td></tr>
<tr><td rowspan="2">Construction Factory (A&R)</td><td colspan="2">Construction factories are employed slightly more than before because of the higher monopolization level on the construction market.</td><td rowspan="2">Construction Factories' application remains its status in the 2010s, rare in the Netherlands.</td></tr>
<tr><td></td><td>The CF is smarter and connected with the controlling AI, enabling the operator to monitor the whole CF system in real time.</td></tr>
<tr><td>Bottom-up System (A&R)</td><td colspan="3">Bottom-up systems are widely employed to do the projects in historical and dense urban environments more efficiently, without using heavy equipment such as cranes.</td></tr>
</table>

5.4.2 Safety management

General

Without considering the legal requirements, large enterprises are more willing to invest in safety management than small ones. Generally speaking, the risk of being injured for each onsite worker is more or less the same; thus, with more workers, big contractors are facing greater risks than small ones. Besides, because of the scale economy, the cost spent on each employee will be lower for big companies (Interview 6). Thus, in Scenario 1, which have more large enterprises (see section 5.3.1), the demand for safety management will be stronger than that of the other two scenarios.

At the same time, as described in the scenario narratives, in Scenario 2 and 3, the number of onsite workers would be significantly reduced (see section 5.3.2 and 5.3.3). In these two scenarios, construction safety management will see the great transition. The main purpose of safety management will transfer from worker protection to efficiency enhancement. Onsite accidents, for instance, collisions between equipment, or falling of cranes, causes breaks and reworks to the project, causing financial losses and longer construction periods.

Virtual reality (VR/AR)

VR has already been employed in the construction industry in many fields. For instance, in property selling, the clients could virtually walk around the buildings they are going to buy to experience (Interview 6). In the past, the main barrier to VR's application was that the high price for devices; however, now, the price has been reduced to a personally affordable level. Now some safety consultant companies in the Netherlands, are trying to employ VR in safety training, for instance, Volandis[6] (Interview 5). It is expected that the VR's employment will boom in the recent future (Interviews 6).

In Scenario 1, more big companies are in the construction market, who are more willing to invest in safety management, including safety training and planning. Virtual reality is a powerful tool in both of the two fields. Thus, it is likely that VR will come across an increase.

In Scenario 2 & 3, due to the greatly reduced onsite workers, VR will continue to be employed in onsite safety training but will be limited on a small scale. Therefore, VR's application in safety planning will decrease.

The probable evolvements of Virtual reality in different scenarios are summarized in Table F.10 (Appendix F).

Augmented reality (VR/AR)

In the Dutch construction practice, AR has not been widely used to assist the safety works on sites, although some attempts have been seen (Interview 6). The main barriers include the high initial cost, and the current AR devices still do not completely fit the onsite application. For instance, the AR glasses now are heavy and cumbersome, sometimes the wireless transmission of data is blocked. However, these technical issues are being solved, and it is expected that it could be technically feasible in very few years (Interview 6).

The future development of AR in construction shares a similar path with VR. In Scenario 1, there are more big companies on the market and the more human interventions in the construction activities, promoting the demand for the technologies that could enhance onsite safety. Therefore, AR's implementation will probably increase. In Scenario 2 and 3, the technology will still be employed, but as the onsite workers are greatly reduced, its

[6] A half knowledge institution focusing on construction health and safety, providing service of consulting and training.

application will be limited on a small scale.

The probable evolvements of AR in different scenarios are summarized in Table F.11 (Appendix F).

BIM

BIM has already been employed to contribute to the safety management in construction processes. For instance, by providing the layout of floor plans, BIM helps to figure out the openings on floors. Then the related information will be sent to onsite operators, via AR devices. Another example is that BIM provides spatial data to VR devices to formulate the virtual environments for safety training.

The fundamental driver of BIM's application is the digitalization and integration of the of the safety information management, and this trend is very likely to continue in all the three scenarios (Interview 6), driving the employment of BIM in safety management. Similar to assembly works, the major barrier to BIM's application in safety management the lack of imagination about how to use BIM in the safety management (Interview 6).

The probable evolvements of BIM in different scenarios are summarized in Table F.12 (Appendix F).

Virtual Prototyping (Simulation, S&A)

Virtual prototyping could be employed in safety management to simulate the construction process before it started, to identify the potential risks. It is something new for the Dutch construction industry. In some states in the US, similar simulation has already been legally mandatory, if the scale of a project is above a minimal line (Interview 5). In the Netherlands, it has not been compulsory for construction activities.

In all the three scenarios, VP is probably to develop greatly for two reasons. First, virtual prototyping method has remarkably improved construction safety performance in some tests (Fang & Cho, 2016). Second, the application of virtual prototyping highly depends on a platform that integrates related information; BIM is able to act like such a platform, and it is already widely employed in the design phase, preparing for VP's use in the future.

The probable evolvements of VP in different scenarios are summarized in Table F.13 (Appendix F).

Internet of Things (IoT)

IoT in construction safety management is mainly employed to monitor the location of onsite objects, including the workers, buildings materials, as well as equipment, to detect the proximity to avoid possible collisions and alarm the related onsite workers to avoid them.

In scenario 1, as discussed in the previous section, the demand for construction safety will increase, and no technical issue impedes its application. Therefore, its application will continue to boom. In the other two scenarios, because of less on-site construction works, the IoT is mainly employed to detect the collisions between non-human objects to avoid potential financial loss and time waste.

The probable evolvements of IoT in different scenarios are summarized in Table F.14 (Appendix F).

Gestures monitoring system (Internet fo Things, Big Data; IoT, BD)

Gesture monitoring system is employed to record and analysis the pattern of workers' movement, to reveal the covert on-site hazards; it also helps to identify the incorrect gestures of workers that may cause MSDs (Musculoskeletal Disorder). Two technologies are involved: IoT, which is used to record the pattern of onsite workers' movements, and Big Data, which compares the recorded data to normal data, to reveal the possible risks. The system is new for the safety practice in the Dutch construction industry (Interview 5, 6). The new method requires high initial costs for the devices and personnel training. Besides, the results of measurement are still not accurate (Alwasel et al., 2013; Yang et al., 2016).

In Scenario 1, this technology's future depends on its technical process. If it could be technically and financially feasible, it will probably be implemented widely. In scenario 2 and 3, similar to the situation of AR, due to the significantly reduced on-site works, the devices can hardly be fully used, making the investment in this field not financially feasible for the contractors. They may choose to purchase gesture monitoring service on the market when they have demand.

The probable evolvements of Gesture monitoring in different scenarios are summarized in Table F.15 (Appendix F).

Summary

According to the previous analysis, the three scenarios of future robotic technologies in construction assembly is summarized in the following table.

Table 5.5. The scenarios of future landscape of the technical innovations in construction safety management

<table>
<tr><th></th><th>Scenario 1</th><th>Scenario 2 and Scenario 3</th></tr>
<tr><td>Virtual Reality
(VR/AR)</td><td>VR is intensively used in safety training, enabling the employees to be familiar with the onsite environments in an offsite circumstance. It is also employed in the safety planning phase by safety engineering to detect the possible risks in the first-person-view.</td><td>VR is still employed in the safety training, but as the on-site human workers have been greatly reduced because of the involvement of AI, the demand for safety training is also reduced.
Most of the safety planning works have been taken over by AI, and human workers are only responsible for checking these works, which does not necessarily require VR.
Therefore, VR will decrease in Scenario 2 and 3.</td></tr>
<tr><td>Augmented Reality
(VR/AR)</td><td>AR is the most popular technique to remind and alarm the hazards on-site. Workers could see the zones with potential risks of falling, burning, collision, etc., to avoid or be careful when approaching them.</td><td>AR is employed to indicate hazards to the on-site operators, but similar to VR; the reduced on-site human workers limit the scale of its application.</td></tr>
<tr><td>BIM</td><td colspan="2">BIM has been widely employed in the construction industry, integrating the information into each project. Based on that, BIM could assist all the related activities in construction safety management, for instance, provide the position of the openings on floors to AR devices so that they can display the information to the onsite operators.</td></tr>
<tr><td>Virtual Prototyping
(S&A)</td><td colspan="2">Virtual Prototyping will be a critical step in safety planning for construction. It simulates the construction process, using the 3D and 4D information from BIM, to identify the possible risks in the process.</td></tr>
<tr><td rowspan="2">Internet of Things (IoT)</td><td colspan="2">IoT is used to detect proximities in the construction process, to avoid potential collisions.</td></tr>
<tr><td>The main purpose of proximity detection is to protect workers from casualties.</td><td>The main purpose of proximity detection is to avoid onsite accidents, which may break the construction.</td></tr>
<tr><td>Gesture monitoring
(IoT and BD)</td><td>Gesture monitoring systems are used to capture the patterns of onsite workers' motion and compare the pattern with the normal pattern in the database, to identify the uncommon motions, which may indicate covert hazards or the risks of MSDs.</td><td>Gesture monitoring systems are relatively expensive. With fewer onsite works left for human workers, the cost for devices and training cannot be covered by the benefits it brings. Therefore, they probably will choose to purchase service on the market.</td></tr>
</table>

5.5 Narratives of the future technologies in construction

5.5.1 Scenario 1: LEGO WORLD

In Scenario 1, construction-assembly works and safety management are characterized by the following features.First, the informatization level in construction is high, helping to improve the performance of building activities. BIM takes an important role in construction activities, providing all the related information to support the construction activities; various techniques are employed to enhance the onsite workers' awareness of information, for instance, Augmented Reality and Cloud Computing. These techniques play important roles in both construction-assembly works and onsite safety management.

Second, the Internet of Things (IoT), using the wireless sensing techniques, connect all the objects on the construction sites, enabling to monitor their positions and status in real time, helping the manager of the project to work more efficiently.

Third, more application of robots makes cooperation between human workers and robots/machines necessary, the Human-Robots Interaction techniques are required.

Finally, conveying equipment develops to the direction of large-scale. Because of the high integration level in the construction industry, standard and branded building modular are widely used, especially in the buildings containing numbers of identical units, such as dormitories, hotels, and apartment complexes. The branded modular sometimes is as big as a room, requiring large equipment to handle.

Herman is an onsite construction manager, working for the construction company LAB[7], which is one of the biggest companies in the Dutch construction industry. LAB's business covers a broad spectrum, including designing, engineering, building, even operation, and maintenance. The project Herman is working on is a student apartment, a small tower containing 50 studios. The building is constructed in a highly modularized way.

Every morning, Herman goes to the construction site, receiving the components needed. When they are delivered, the tags attached to them are scanned. Thus they are included in the 'Internet of Things' on the construction site. This onsite internet also includes the workers and equipment. It is monitored in real time, and the information of the objects could be read by Herman via the central monitor.

4D BIM provides the information of construction process. Herman reads this information and divides the process into different tasks, then designating them to specific workers. As soon as a worker is assigned a task, an instruction will be sent to his mobile device, e.g., tablet, or helmet integrated with AR devices. For instance, one component will need to be assembled in 10 minutes; by viewing the list of labors in IoT, Herman finds that Tom will be available in ten minutes. Then he assigned the task to Tom, who will then read the instruction on the AR screen of his helmet.

When Tom starts the task, the helmet displays the related information to him intuitively. The AR glasses indicate the location of the component in the stockyard, its final position in the building, as well as the most optimized path calculated by the specific software. Along the path, with the assistance of handling robotic system, Tom send the component to the right place and refine its position until it is aligned with virtual image showed by AR. For some large components, handling robots and traditional construction cranes are not proper anymore, and gantry cranes which used to convey containers are employed to handle them.

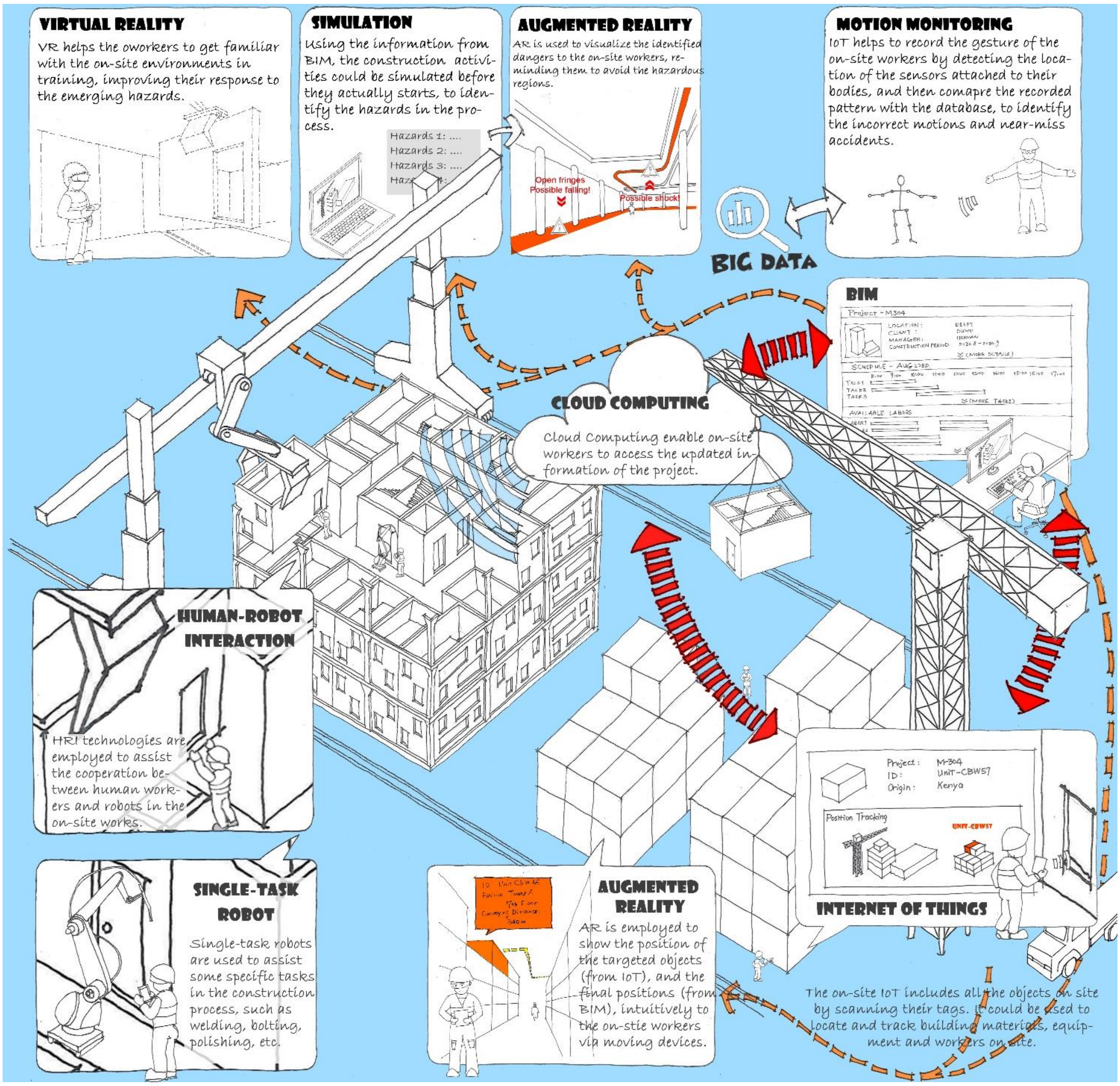
When the component is in position, single-task robots are used to help to connect the components to the existing structure. The whole process is monitored by cameras on drones. When the monitoring system detects the task is finished, Herman

[7] A fictional company.

will mark it as 'completed'; and on the controlling panel of IoT, Tom's status become 'available' again. Then inspection process is started, a drone with a laser scanner or photogrammetry scanner are sent to the place, getting spatial information and building a digital model of the as-built environment, then comparing it with the designed model, inspecting whether the component is assembled as designed.

Before the project starts, the construction process is digitally simulated, with the information provided by 4D BIM. This simulation helps to identify the potential hazards. In the construction process, these hazards will be displayed to the workers on their AR glasses, for instance, the fringes where falling may happen, the pipes that should be avoided, potential collisions with equipment, etc. Before beginning to work onsite, both the managers and labor workers have accepted safety training in virtual reality environments, which helps them to get familiar with the safety issue on construction sites. For each labor worker, multiple sensors are attached to different parts of his body, so that his motions could be recorded and analyzed, to identify the gestures that may cause chronic damages to their muscle and skeleton system.

Figure5.7. The future landscape of technologies applied in a project in Scenario 1



5.5.2 Scenario 2: SMART TIMES

In Scenario 2, several characteristics in the construction assembly and security management works of the project could be observed. First, the combination of AI-BIM takes the central place in the organization of the project and controls the whole project via the onsite IoT. AIs replace human onsite, therefore, the technologies assisting human workers to improve their performance have decreased, such as Augmented Reality and Human-Robot Interaction.

Second, because of the application of AIs, robots, and equipment do not rely on the preprograms embedded in them anymore, but on the real-time instructions of the controlling AIs, thus the construction robots do not need to be designed for specific tasks. Swarm robots, which are standard and multi-functional, replace single-task robots. They could finish simple works individually, and work together to handle complicated tasks. Controlled by AIs, they are able to deal with the working environments more precisely and pertinently, replacing the human labors in almost all the tasks onsite.

Finally, as human workers are very rarely involved in onsite works, the onsite security management mainly focuses on avoid accidents may lead to pauses of the project and financial losses.

Linda owns a small building company. Her company has only five staff, including herself. Thanks to the application of AI, small contractors could do more works than ten years ago. For instance, all the paper works in her firm are handled by the 'virtual Secretary', an AI app; besides, AIs also involve in the construction works, working as controllers and executors, while human workers play the role of supervisors, rarely intervene the projects. Now Linda is working on a small project, a detached house in Utrecht.

With the assistance of BIM, AI is the controller of the whole project, organizing and managing. At the beginning of the project, AI got all the related information of the project, including the BIM model, the construction schedule, the supply chain, etc., according to which the AI organizes the construction activities.

With the information related to the construction schedule, the AI prepares orders for needed materials. Linda then checks these orders before the AI send these orders. Every morning, when these materials and components are delivered to the construction site, AI controls the robots and equipment to offload the materials. At the same time, the tags attached to them are scanned, so that they are included into the onsite IoT, and the controlling AI could track and manage them. Then they are placed on the stockyard according to their assembling sequences. After the offloading is done, Linda confirms the reception, which legally cannot be done by AIs yet.

In the construction process, the controlling AI decomposes the construction schedule into specific tasks and designates these tasks to the specific robot(s) or equipment. For instance, specifically in construction-assembly works, conveying the materials to be assembled, place the materials and connect them to the existing structure, etc. When dealing with big components, smart equipment is employed. BIM provides necessary information related to these tasks, e.g., the ID of the components to be assembled, its weight, location, the destination to which it should be conveyed in the building, etc. Using this information, the AI generates instructions for the executing robots and equipment, and transmit the instructions to them via the IoT, by wireless sensing technique.

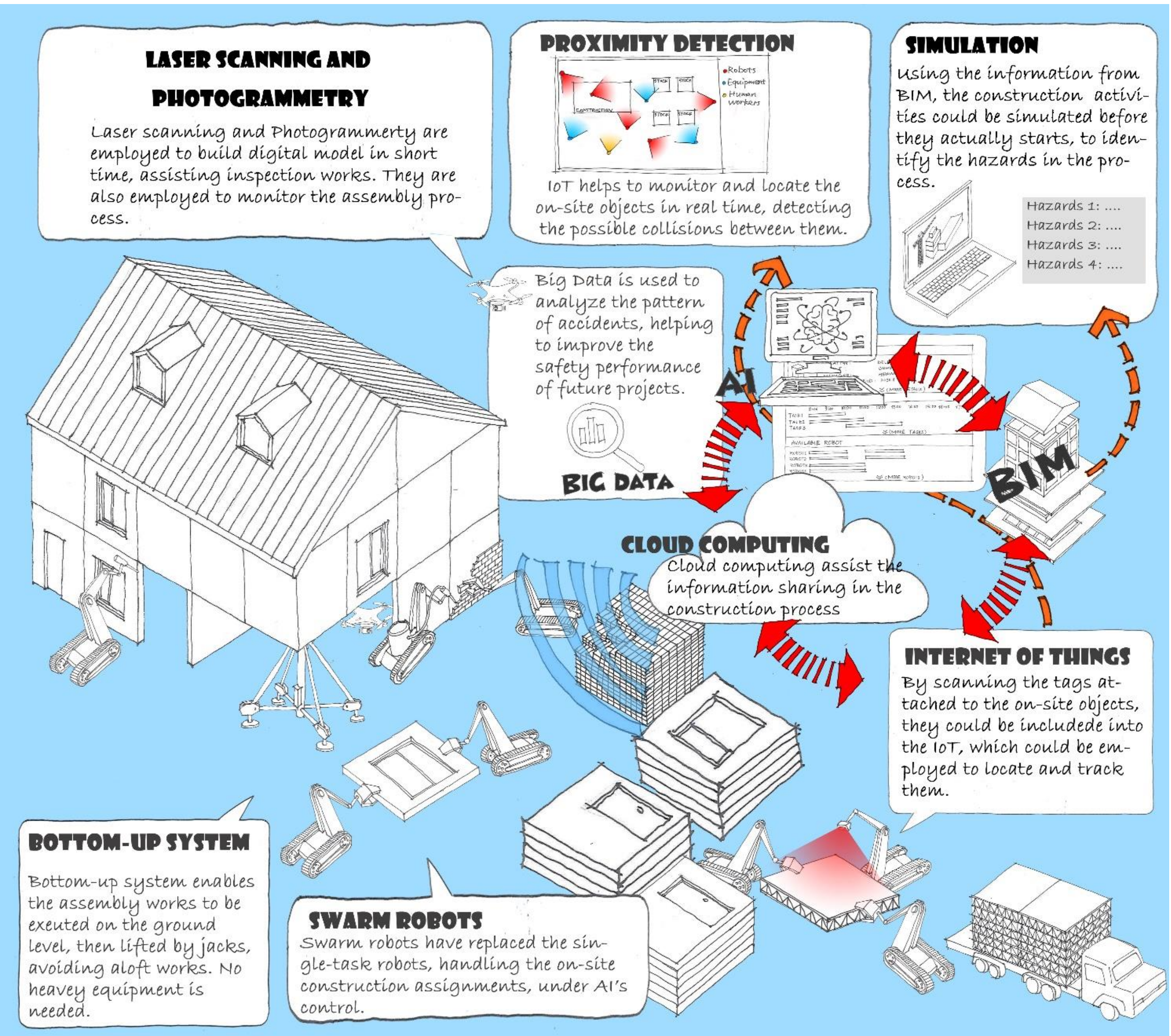
The IoT also includes onsite sensors and cameras, some of which are fixed and some others are carried by robots, equipment, and drones, moving around the site. These sensors and cameras transmit the real-time information of the construction site back to the controlling AI. With the IoT, the controlling AI could get a full picture of the whole construction site, which helps its decision making in the construction process.

In the inspection phase, drones carried photogrammetry scanner moving around the site, to build up a spatial model of the finished works. Then the model is compared with the BIM model, to check whether the assembly work is done as designed.

In this project, the bottom-up system for construction-assembly works is employed. After the earthworks were finished, the roof of the house was first assembled by the robots on the ground level, then pushed up by hydraulic jacks; then the first floor was assembled and lifted, now the ground floor is being assembled. This system keeps the assembling works always on the ground, making the working environment more proper for robots and equipment.

The techniques to protect human workers' security in construction, such as VR and AR, are much less employed because human labors are very rarely involved in the onsite execution, and the security management mainly focuses on avoid accidents may lead pauses of the project and financial losses. For instance, before the project started, a virtual prototyping process had been run to simulate the construction process, focusing on identifying the potential accidents; BIM provides 4D information for the simulation. Besides, the onsite IoT could track all the onsite objects in real time, including building materials, robots, and equipment; with particular software, the proximity between them could be detected and an alarm will be turned back to the controlling AI to avoid collisions.

Figure5.8. The future landscape of technologies applied in a project in Scenario 2



5.5.3 Scenario 3: PARADISE

Scenario 3 is more like a combination of the previous two scenarios, the following features are reflected in the assembly works and onsite safety management. First, the AI-BIM combination performs as the controller of the project, using IoT to manage the project, while the human workers act as supervisors. IoT on the construction site helps the AI to track and control the objects on the construction site.

Second, large-scale equipment is employed to handle the modular in big size; swarm robots replace human workers and single-task robots in the construction process.

Finally, similar to Scenario 2, because of the rare human intervention in onsite works, the techniques aiming at enhancing human workers' awareness of hazards almost disappear in onsite safety management, such as AR, VR and Motion Capturing. The main focus of this type of works is to keep the project going on without emergencies that interrupt the construction process.

Henk works for a building company. The company used to be a big one, with thousands of employees. Now, however, with the application of AI and robots, the number of employees is decreased greatly. Now for each project, according to the scale, only a few human workers needed to be responsible, mostly for the works that require officially legal status to finish, such as signing the deliverables, approving the schedule made by the AI, confirming the results of inspections, etc.

Henk is working on a project of an office tower. The design of the building adopts a lot of branded modular, e.g., the toilets, staircases and elevator shafts, integrated slabs which contain ceiling, pipes and net floors, and the modular of the curtain wall. In this project, the controlling AI, with the assistance of BIM, control the project. It monitors all the objects in the project via the onsite IoT; generates construction schedules for the project; distribute the tasks to proper robots and equipment; send related information and instructions to robots and equipment so that they can finish the tasks. BIM supports the AI to manage these works, by providing related information.

Onsite Construction Factory is employed in the project. Large structures are built to support a roof for the construction site, under which is a semi-indoor working environment, on the top of the tower being built. It is less affected by weather, therefore a relatively stable working circumstance. Envelopes could be attached to the structure to shield the effect of the weather further, if necessary.

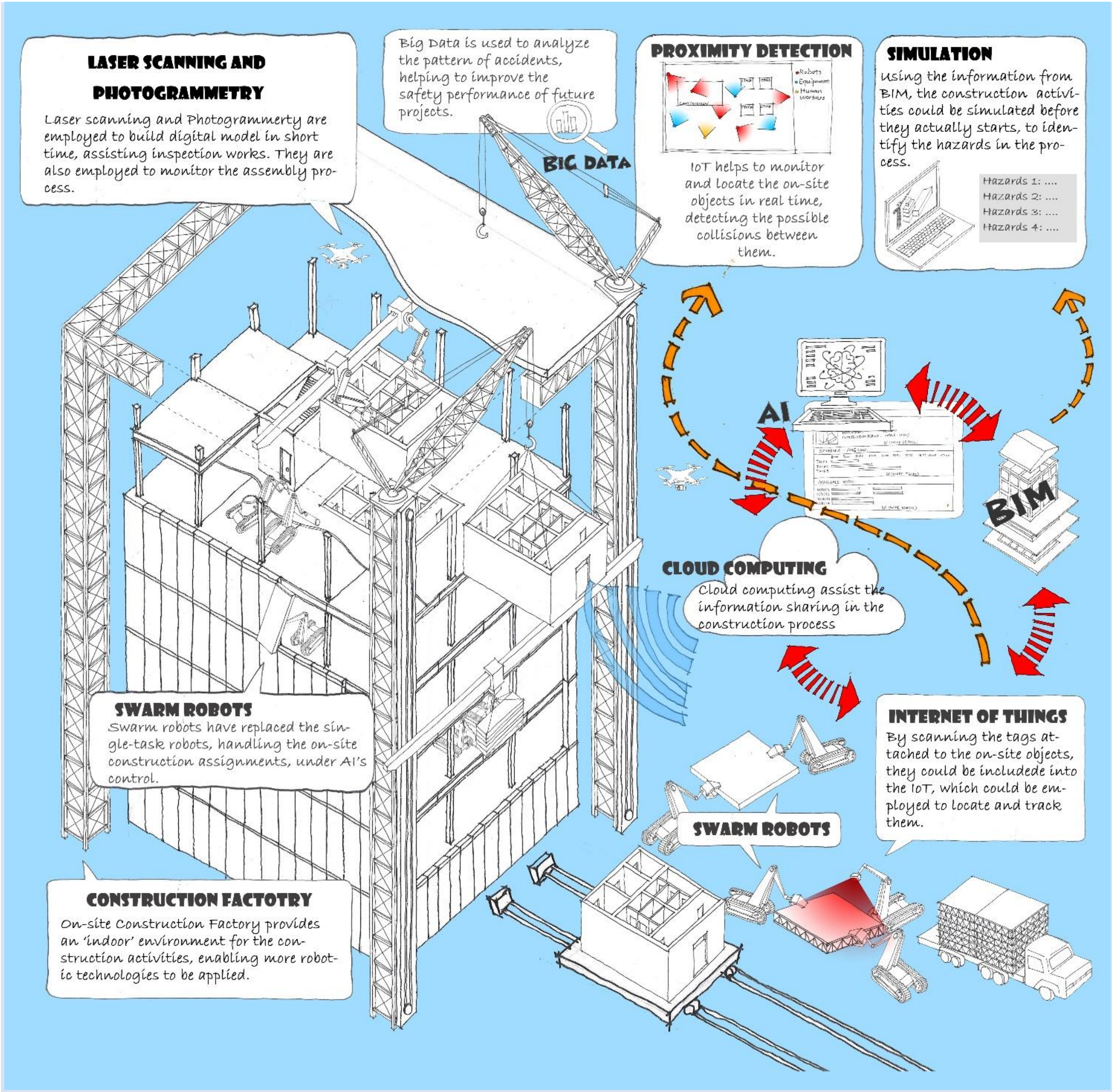
Robotic handling system is applied with the CF. On the under surface of the 'roof' fixed rails for horizontal conveying hoists. The big modular is lifted by cranes and then handed over to the hoists moving horizontally, being carried to its final position. When the main structure of each floor is finished, the roof automatically rises to build the upper floor. The r vertical hoists are used to lift the smaller components or building materials to specific floors, where robots will hand over. Compared with the traditional cranes, this system is more efficient.

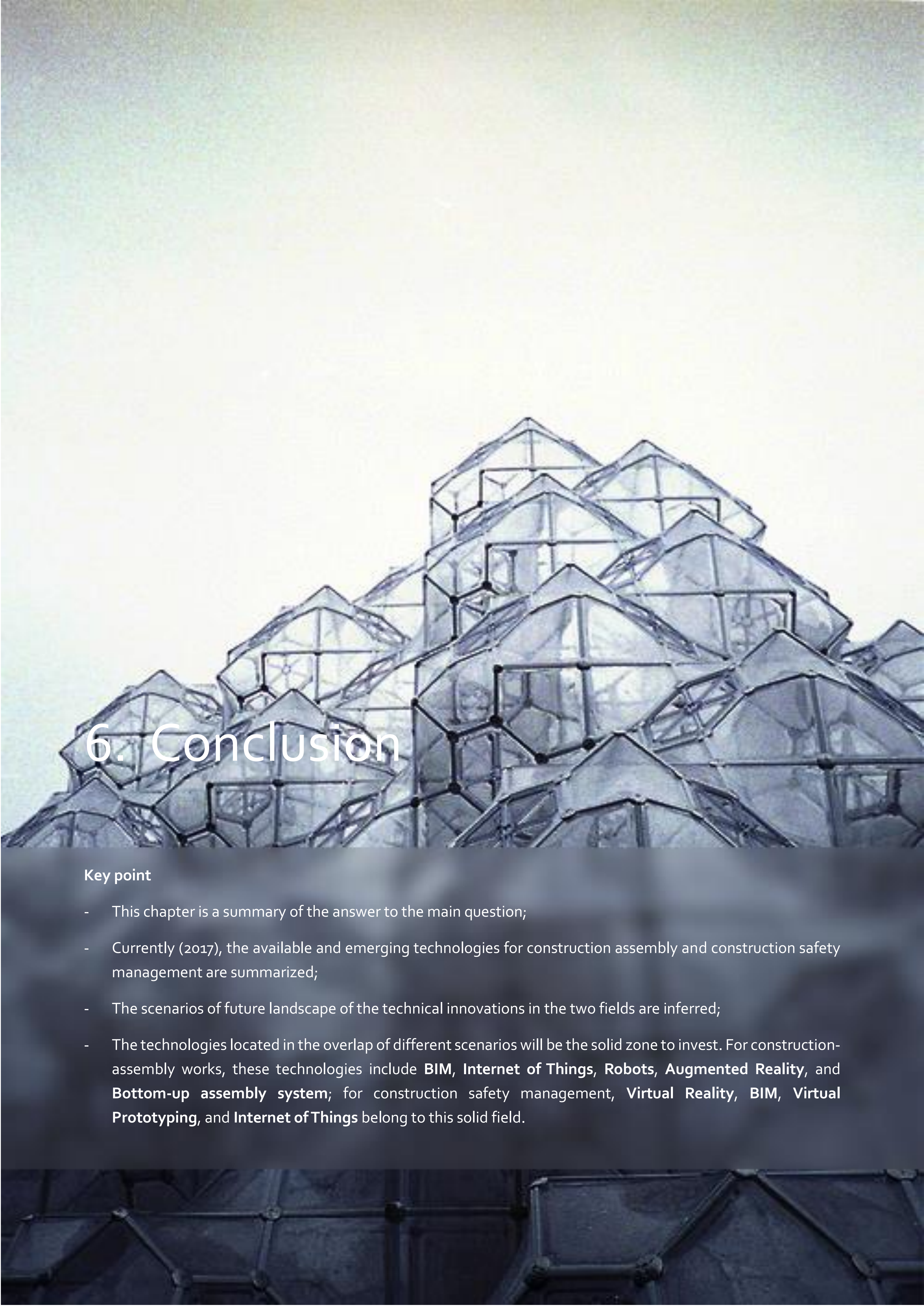
Swarm robots are employed to execute the onsite works, including offloading and scanning the building materials, assembling the curtain wall, connecting the pipes in integrated slabs, polishing the floor, finishing the interior, etc. In the processes, they receive instructions from the controlling AI, and also send back the real time situation to the AI to assist its decision making.

Laser scanning and photogrammetry scanning are employed in the inspection works.

Security management in Scenario 3 also benefits from the IoT, which helps to track the onsite objects to avoid collisions; and virtual prototyping is applied to simulate the potential risks. All these safety measures require the spatial and construction sequential information of the project, which BIM provides.

Figure5.9. The future landscape of technologies applied in a project in Scenario 3





6. Conclusion

Key point

- This chapter is a summary of the answer to the main question;
- Currently (2017), the available and emerging technologies for construction assembly and construction safety management are summarized;
- The scenarios of future landscape of the technical innovations in the two fields are inferred;
- The technologies located in the overlap of different scenarios will be the solid zone to invest. For construction-assembly works, these technologies include **BIM**, **Internet of Things**, **Robots**, **Augmented Reality**, and **Bottom-up assembly system**; for construction safety management, **Virtual Reality**, **BIM**, **Virtual Prototyping**, and **Internet of Things** belong to this solid field.

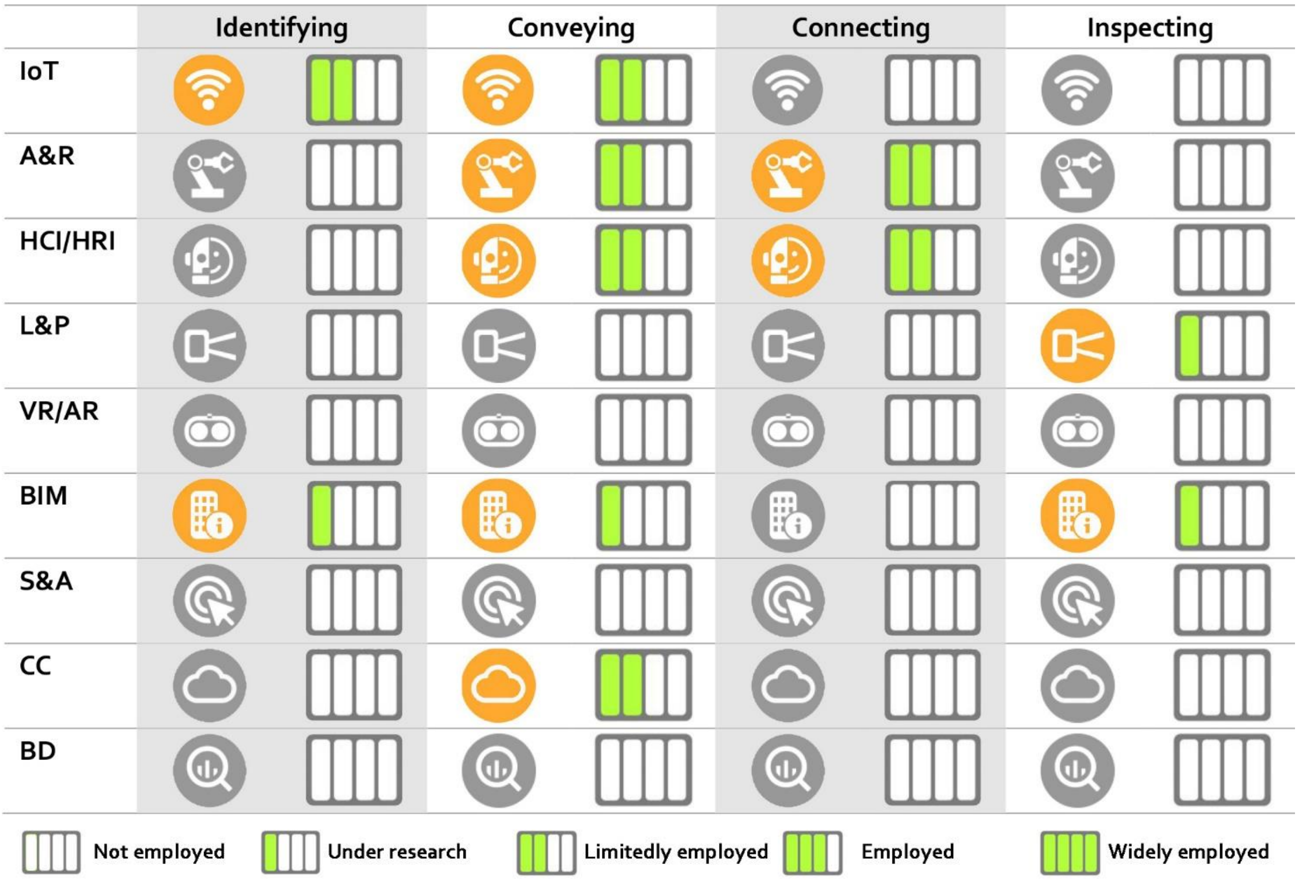
6.1 Currently available technologies

6.1.1 Construction-assembly works

Currently, the robotics level of construction assembly in the Dutch construction industry is quite low. Although some of the technologies identified by literature study have applied in pilot projects in the Netherlands, none of them is implemented on a large scale. Some of these technologies are both technically and financially feasible, and the most major barrier for their application is the conservativeness of practitioners and the lack of imagination.

Among the clusters of technologies identified in Chapter 3, six have been applied in construction-assembly works, or at the prototyping phase. These clusters include IoT, Automation and Robot (Handling Robots, Single-Task Robots/Robotic System, Construction Factory, Bottom-up System), Laser Scanning and Photogrammetry, BIM, and Cloud Computing (Figure 6.1). Details could be found in Table E.1 (Appendix E).

Figure 6.1. Technologies in construction assembly

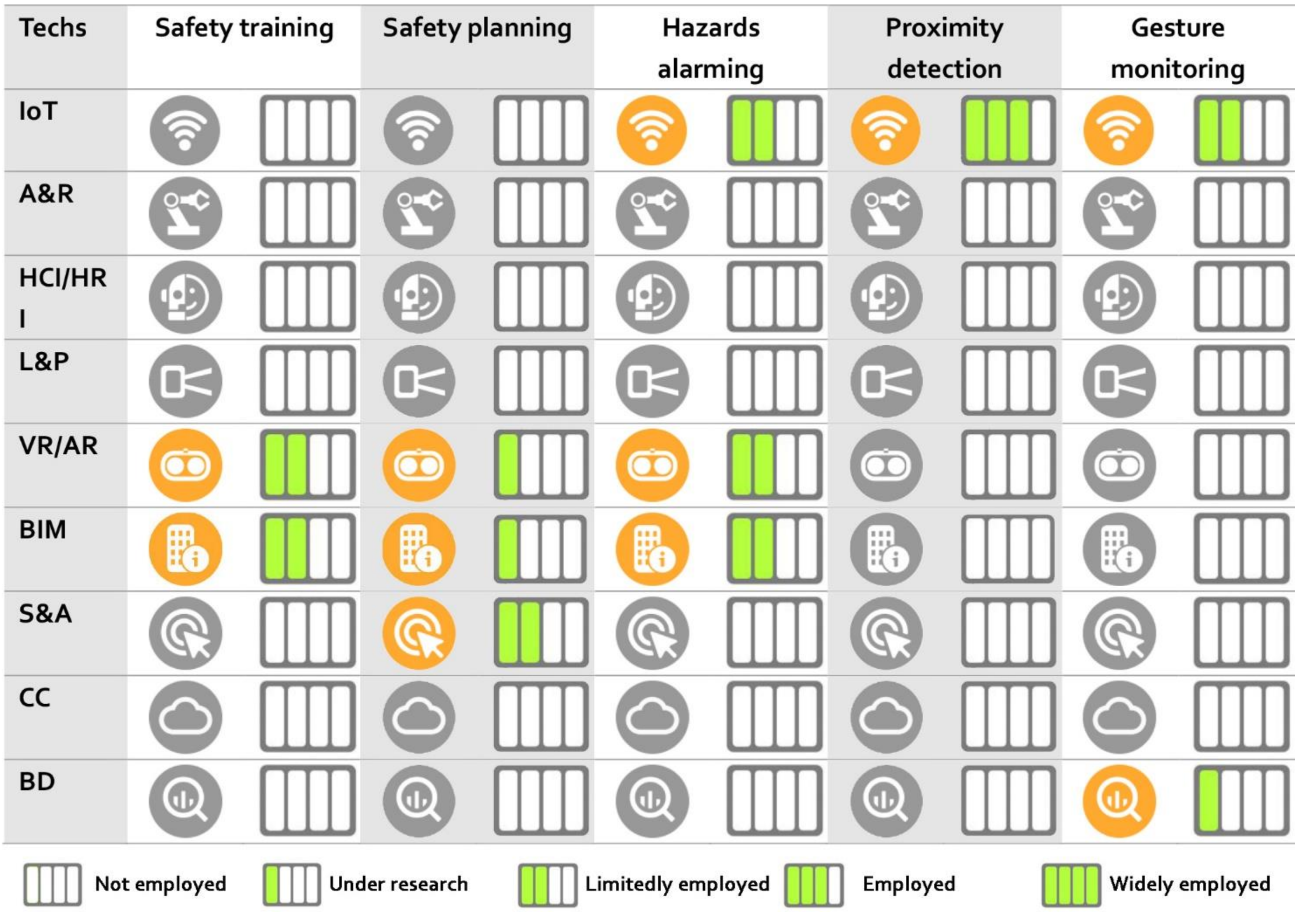


6.1.2 Safety management

As a 'second type work', safety management is a relatively new field of construction robotics. Unlike the first type works, safety management does not involve many heavy and repetitive manual works. Its essence is the management of hazards information, including collecting information, processing information and sending the information efficiently to the related on-site workers to avoid the hazards. Therefore, the mostly applied technologies in this field are those related to information management. Meanwhile, those 'traditional' mechanical technologies are very scarcely applied.

Five of the elven identified clusters of technologies in Chapter 3 are employed in the construction safety management, including Internet of Things (Wireless Sensing, Wearable devices), Virtual Reality and Augmented Reality, BIM, Simulation and Algorithm (Virtual Prototyping), and Big Data (Figure 6.2). Details could be found in Table E.2 (Appendix E).

Figure 6.2. Technologies in construction safety management



6.2 Future landscapes of the technical innovations

In Chapter 5, three scenarios have been established. This section discusses the possible futures of the technical innovations of construction-assembly works and construction safety management in the three scenarios respectively.

6.2.1 Scenario 1: LEGO WORLD

In this scenario, the integration level of the construction industry has been developed greatly. Meanwhile, the other factor which is used to construct the scenarios, Artificial Intelligence, has not got significant development. In this scenario, more big companies dominate the construction market, integrating all the phases in the building activities, from design, building, to operation and maintenance. As a result, the small, daily life buildings (e.g. residential houses) have been brandised, similar to the situation in the car and cell phone industries. Standard products take a large share of the market, which are designed by the suppliers, and partly built in the globally-distributed producing system. Then the modular and components are sent to clients' site to be erected. This trend also affects the large and complex buildings. Although they cannot be completely standard, the major suppliers on the construction market try their best to construct these buildings using the standard modular they produce, for instance, the staircases, bathrooms, and toilets. Human workers still play an important role in the construction activities, as AIs are still not powerful enough to take over the most of the works.

BIM stands in the central place in construction-assembly works. It provides spatial and sequential information of the projects, supporting assembly processes. For instance, it gives the information about the final location of a specific component so that its most convenient conveying path could be calculated; BIM also provides the assembly sequence, helping the managers to order the materials needed for the projects. With the on-site Internet of Things (IoT), the information and video guides could be distributed to the related workers, being displayed to them intuitively on the screen of AR devices. Thus, the efficiency of construction assembly is enhanced. Robots are employed in the whole process to assist human labors. Compared with twenty years ago, they are much smaller and lighter, therefore easier to be used. Human-Robot-Interaction technologies are used to improve the cooperation between human beings and robots. High modularization level brings many large components, and large handling robotics are employed to handle them, such as gantry cranes. As the large companies dominate the market, Construction Factories are implemented more than before. The Bottom-up systems are implemented to some extent. In some inspection works (for instance the assembly of MEP devices), laser scanning and photogrammetry are employed to quickly construct a digital model of the built environment and compare it to the BIM model, to assist the inspecting process. The data of the whole assembly process in a project is collected by the IoT on site. The Big Data analysis provides some information for project management and decision making. For example, when a manager is trying to plan a path for a component to be conveyed by simulation, the paths of other materials, equipment and workers are necessary for the simulation to avoid collision and congestion; Big data helps to analysis the related information. Analysis of the inspection data helps to figure out the works in which flaws may happen; Cloud computing is employed in the process, helping each part of the project can access the updated information through the cloud databases.

In the field of safety management, similarly, BIM and IoT also play the most significant roles, because they are responsible for information provision and distribution. Using the information of the construction activities provided by BIM, specific software helps to simulate the building process and identify the possible dangers. Virtual Reality (VR) helps the safety managers to observe the construction site to find more hazards. Then AR devices connected to the IoT display the potential hazards visually to the workers to enhance their awareness. The IoT at the same time monitor the real-time location of all the objects on site and their proximity, to avoid collisions. Big Data is employed to analyze the motion of on-site workers to detect the near-miss accidents and correct their gestures to avert Muscle-Skeleton Disorders (MSDs). It also could be used to analyze the hazards data, to figure out the pattern of dangers, feeding back the results to the cloud database, to assist safety planning in future projects.

6.2.2 Scenario 2: SMART TIMES

In Scenario 2, Artificial Intelligences have developed so significantly that they can take over the management of construction activities, and human workers play the role of supervisors. Almost everything is automatic, making it a ‘Smart times’. Information technologies, therefore, play a crucial role in this scenario. Robots are employed to execute the onsite works which were done by human labors in the past. Thanks to the assistance of AIs and robots, construction companies can go with fewer employees than before. Therefore, many small companies survive and are active on the market. On the other dimension of the scenario-planning matrix, the integration level is relatively low. The construction industry keeps on the original path, highly depending on the on-site works.

In construction-assembly works, similar to Scenario 1, the combination of BIM and IoT takes the central position, providing information, supporting simulation, monitoring the assembly, and collecting data from the process. Robots are widely employed in construction activities to replace human workers. However, different with Scenario 1, the handling robots and single-task robots are replaced by swarm robots, which are standardized and multi-functional, more flexible to organize in projects, and cheaper and easier to maintain. Augmented Reality (AR) and Human-Robot-Interaction (HRI) technologies, which are related to the human workers on site, will continue to be used, but on a very limited scale, because there are scarce on-site workers that require human workers to deal with. Construction Factories' implementation remains the situation twenty years ago, but the Bottom-up system becomes more popular than before. Big data is also employed to support the conveying path analysis and to figure out the pattern of possible flaws' distribution in inspection phase.

In construction safety management, BIM, IoT, Cloud Computing and Simulation contribute most to the enhancement of the performance. As the on-site human workers have almost disappeared, the application of those technologies that related to the safety of human workers' safety are also limited to a small scale. For instance, AR, VR, and the gesture monitoring systems. Big Data used to be employed to monitor the motion of on-site workers; now it is more used to collect it mainly used for the hazards' data analysis.

6.2.3 Scenario 3: PARADISE

In Scenario 3, the construction industry gets progress in both of the two dimensions. Controlled by AI, the construction activities are highly automatic, without too much human intervention. Some construction companies evolve into versatile enterprises, containing inhouse capability of designing, building, operating and maintaining, providing standard products, or semi-standard products, which mainly consists of the standard modular they produce. At the same time, AIs' application helps many small companies to survive. Thus, the monopolization level of the market is medium.

Assembly works in construction mainly relies on BIM and IoT; Simulation, Big Data, Laser Scanning and Photogrammetry also contribute; Cloud Computing helps the different terminals on site (equipment and robots) to share related information in real time. In this scenario. Similar to Scenario 2, the human-worker-related technologies, including HRI and AR, are scarcely used. Both of the on-site Construction Factories and Bottom-up Systems get more used than before.

The technologies applied in safety management in this scenario shares the same landscape with Scenario 2.

6.2.4 Summary

The future of the technologies in construction assembly and construction safety management are summarized in Table 6.3 and Table 6.4 respectively.

Table 6.3. The application of the identified technologies in construction assembly

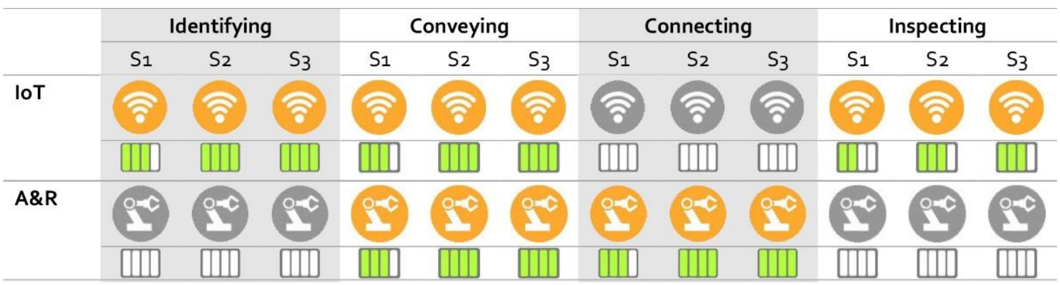


Table 6.3-continued

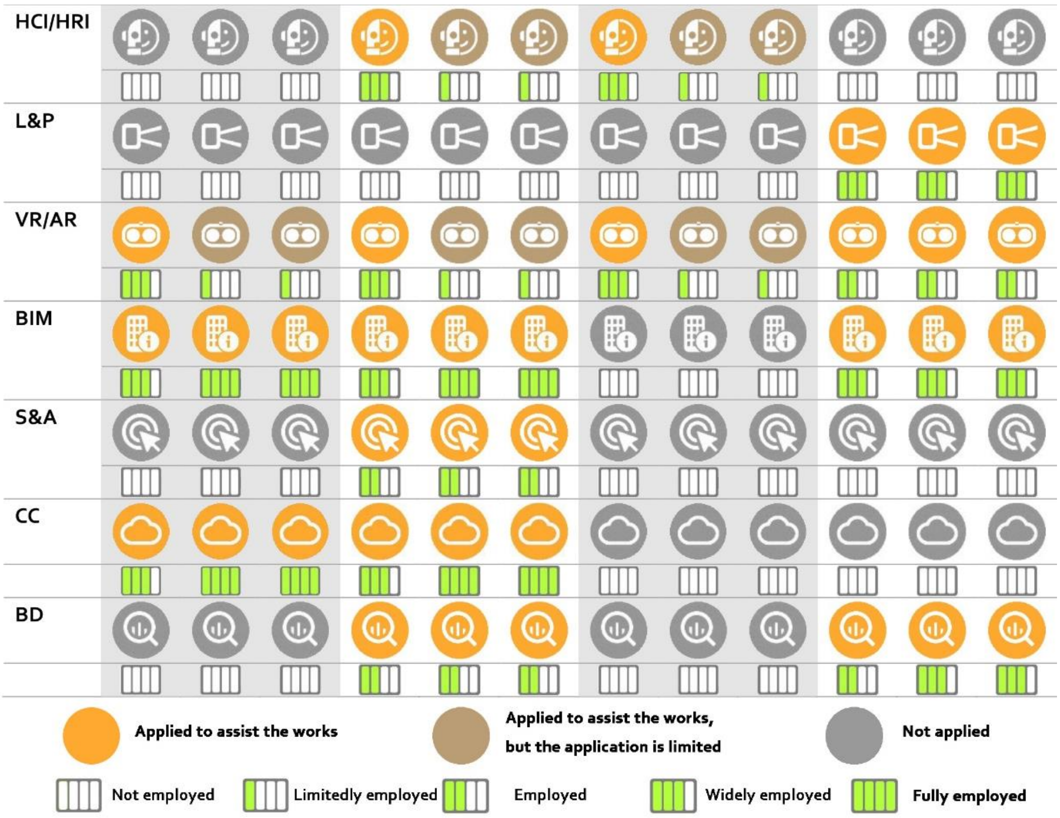


Table 6.4. The application of the identified technologies in construction safety management

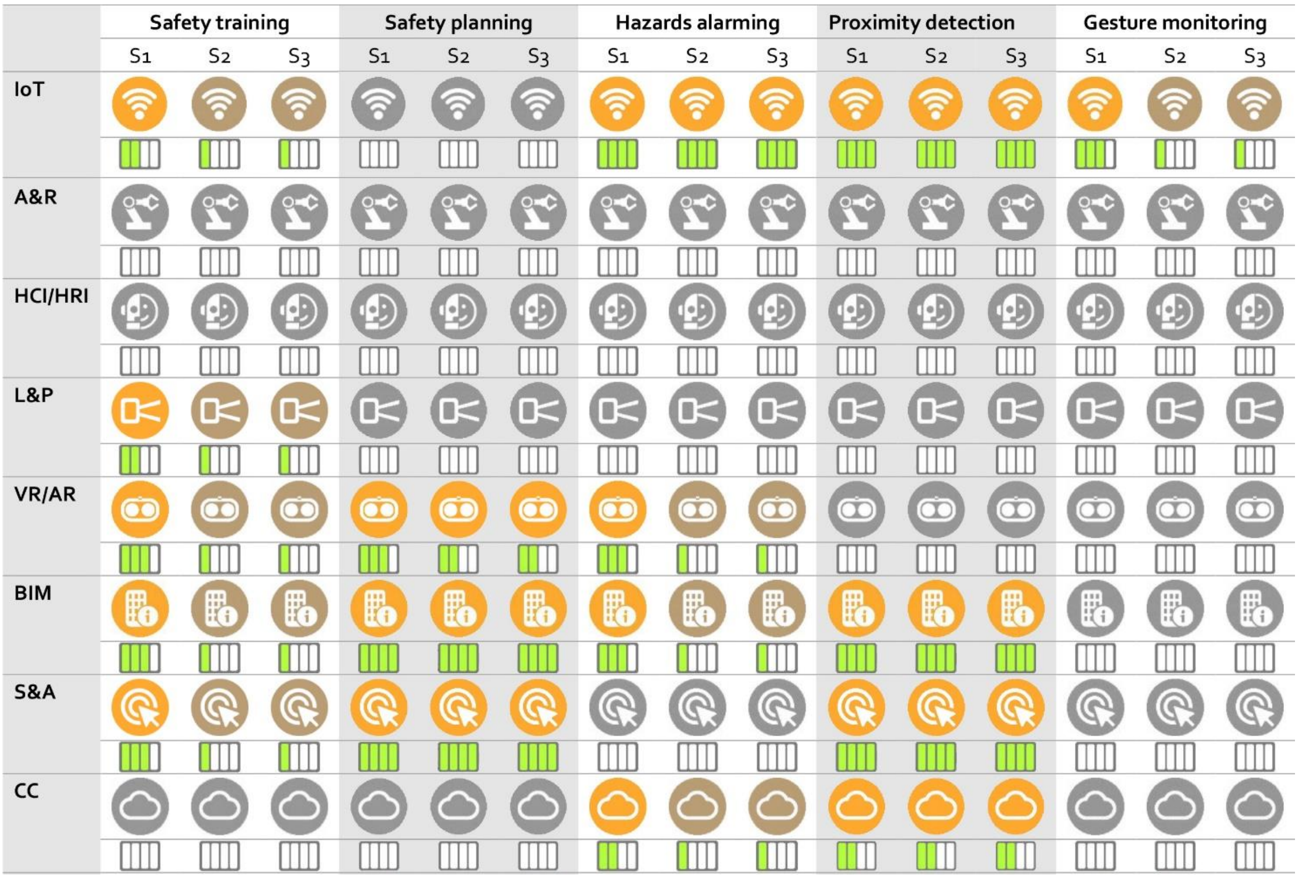
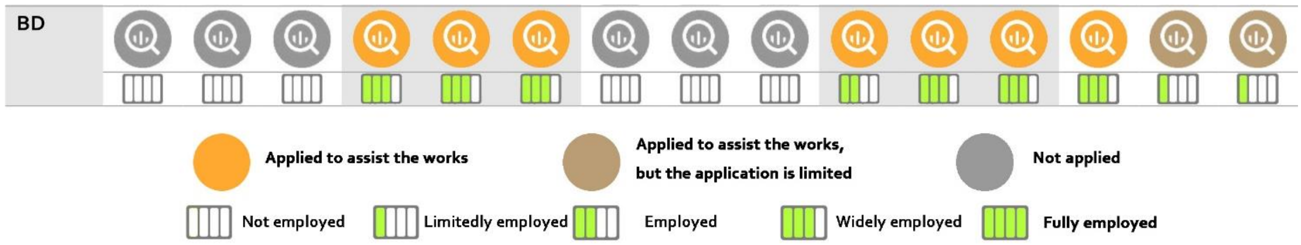


Table 6.4-continued



6.3 Overlaps of the three scenarios

From Table 6.3 and 6.4, it could be observed that in both of the two selected tasks, Scenario 2 and 3 are similar to each other, being quite different from Scenario 1. This may indicate that the factor 'Artificial Intelligence' is more significant than 'Integration of the construction industry'. The overlaps of the different scenarios represent those technologies that will get further developed in all scenarios. Thus, for the practitioners, these technologies are the most solid fields. The investments in these fields, including purchasing devices, training workers, researching and developing related technologies, are less risky.

In construction assembly, these 'safe' technologies include the following items.

- **BIM**. BIM stands at the center of the informatization trend in the construction industry, integrating all information in a project, supporting all related activities in construction assembly.
- **Internet of Things**. IoT connects the objects on site to a network, which helps to collect and distribute data and information, improve the efficiency of the construction activities.
- **Robots**. No matter how automatic construction-assembly works could be, they are, after all, physical processes and require 'executors' to deal with the 'real' works. However, it should be noticed that in different scenarios, robots evolve along the different paths. In Scenario 1, robots become smaller and lighter, and therefore more proper to interact with human workers; in Scenario 2 and 3, swarm robots will replace the single-task robots.
- **Cloud Computing**. The information on construction sites is dynamic. Cloud Computing enables all the terminals on site (workers, robots, and equipment) to access the updated information in real time, enhancing the efficiency.
- **Bottom-up system**. This newly emerging technology aims to improve the performance of small-scale construction activities in densely populated urban areas, which is an important part of the Dutch construction industry.

In construction safety management, with the decrease of on-site workers in Scenario 2 and 3, the demands for safety training, hazard alarming, and gesture monitoring diminishes in these two scenarios. Therefore, the technologies that will play important roles in all the three scenarios mainly contribute to the other two fields (safety planning, and proximity detection).

- **BIM**. Similar to the Virtual Prototyping, information management is the most critical section in safety management. BIM, as an integrated platform, will continue to be applied widely in safety management.

- **Internet of Things**. Safety management requires the information about all the location of on-site objects, which could be collected and updated by IoT.

- **Simulation** (such as Virtual Prototyping). By simulating the construction processes, the potential hazards could be identified more effectively.

- **Cloud Computing**. Cloud Computing technologies assist in sharing information in construction projects.
- **Big Data**. Analysis of the massive data helps the manager or managing AI of the projects to figure out the distribution pattern of potential hazards, and feed the results back to databases, improving the safety performance of the future projects.

7. Reflection

7.1 The graduation project: a long process

Starting from the last September, this graduation project covers quite a period. In the first year of the program, all the courses were finished within two months, while the graduation project lasts nine. After working on the project over an extended period, the initial passion fades off; meanwhile, the more I know in this field, the more leaks I found in the previous works. The whole project is dynamic and iterative: every time I read something that I wrote down earlier, I found many flaws to be fixed to fit new ideas. Therefore, the process is filled with struggling, frustrations, and difficulties. At the same time, it is also a journey of discoveries, surprises, and excitements. Each time a problem is fixed, a fresh idea is got from an interviewee, or a creative solution flashes, the pleasure inspires me to continue on the way.

At the very beginning, I wanted to focus on the relationship between the robotics level of onsite construction works and the prefabrication level, to see whether prefabrication helps to enhance the robotics level of on-site works. I thought maybe it is the prefabrication level that affects robotics level of the construction industry, especially after our excursion to the prefabrication factory in Amsterdam.

In the first draft of the research proposal, I adopted a quantitative strategy, by measuring the levels of robotics and prefabrication in a set of cases, to evaluate the relationship between them. However, this strategy was later proved to be unpractical. First, the defining and measuring of robotics level and prefabrication level are difficult, lacking technical support from literature. Second, projects are unique, which means it is impossible to exclude other factors which may affect the robotics level of a project except for prefabrication level. Therefore, this topic was finally given up.

At the same time, I reviewed the abstracts of the ISARC papers in recent years, to see what are the researchers doing in the construction robotics field. By doing so, I found that, compared with the starting phase of construction robotics, currently the technologies applied in construction are much more diverse, making the whole picture of the construction robotics dazzling, or even confusing. However, there is not an overview of the technologies applied in construction robotics available. Therefore, I generated the idea to make a simple and concise overview of the construction robotics technologies. This overview could also be used by the practitioners as a reference when they are going to adopt new technologies to solve the problems they are facing.

My second mentor, Pieter Stoutjesdijk, suggested that maybe it will be more scientifically and practically relevant to expand the focus from the current status to the future landscape of construction robotics technologies. Therefore, the final research question was decided to focus on the various technologies applied in construction to enhance a higher robotics level, including both state of the art and the state of the future.

7.2 Lessons learned from the process

From the process, some lessons have been learned. They are not only helpful in academic works but also inspiring in life.

To systematically know the field before the project starts

As mentioned in the foreword, I choose the graduation lab construction robotics because of some personal motivation. Then I chose the topic of the relationship between prefabrication and robotization. The choice based on my personal experience, without systematically knowing what other researchers are doing in this field. To avoid the risk of redoing some work that somebody else had done, I also conducted some search on the topic. The topic is by then hardly studied. Therefore, I thought it could work. However, soon after that, I came across difficulties in elaborating the research proposal for the topic: very little related literature and research methods were available to support this topic, making the research more like an air castle. Finally, the original topic was hard to continue and finally given up.

Therefore, knowing the field well is crucial for topic selection. It does not only guarantee that the research work is unprecedented, but also helps to figure out the most proper topic. Scientific research is a collective activity, with many researchers co-operating; generally, each study contributes slightly to the whole structure. The upper part of the pyramid is fine, but supports from related studies are required to reach there. Without a full picture of the field, it is very likely to choose a topic that is not feasible enough.

Research plan need to be adjusted dynamically to adapt to the process

The only constant in the world is the fact that it is changing ceaselessly, the research as well. When the research plan is conducted, many uncertainties impede it from being realized as originally planned. For instance, according to the original plan, in some interviews, interviewees are required to read the narrative I made and then evaluate the future development of each technology in the three scenarios. However, after the first interview, I found that it made the interview lengthy and boring, and also, difficult for interviewees to answer; at the same time, the interviewees do not necessarily completely agree with the narratives. Therefore, the strategy was adjusted, with some more open questions to discuss the three scenarios themselves with the respondents, to establish more reasonable scenarios as the base of future study. The evolvement of specific technologies is later investigated by desk research. It turns out that the new strategy works well. It is important to keep flexible in the work, to handle the unexpected difficulties, getting the best outcome with limitations.

More perspectives help

The involvements of experts with different backgrounds provide different perspectives, which contribute to making the research well-rounded. The interviews come from both practice and academia, concerning different fields in the construction robotics. They observed construction robotics from various perspectives and provided different inputs from their points of view.

Should try better to sell the research

In this research, the future study is based on the scenario planning. To establish the scenarios, some factors that may affect the future development of construction robotics need to be identified. In the initial planning, this process should be done in a workshop with all the participants together, so that they could inspire one another in a brainstorm. However, most of the participants had difficulties in adjusting their timetable to travel to another place during weekdays, therefore, finally, the identification and assessment of the factors are done in an alternative individual way (see chapter 2). Although the new method also works, it is not as ideal as the original one.

This could be done better by improving the 'advertising' of the research. The experts were not willing to adjust their timetable because they were not so interested in the research, only involving in the research from the perspective of 'helping a student to finish his graduation project'. If the invitation could attract them by revealing the potential outcome they may get from participating in the research, maybe they will be more willing to take part in a group work, despite the possible inconvenience it may cause.

Things will never be perfect

There are some limitations in the research. For instance, the future study in this research is established on inferring the possible future evolvement of the currently available technologies in different scenarios. This is only a part of the future technologies, and definitely, there will be some new technologies appearing in the future. However, It is impossible to predict these new technologies, even for the experts; and there is not a solid method to do so. Therefore, it does not make much sense to focus on these technologies, which were finally skipped. Thus, the future exploration is not complete enough, but focusing on the more significative part. Such flaws are difficult to completely avoid in research activities; if currently no proper research method could be found, the best way is to accept it and admit the limitation of the research, leaving it to smarter researchers in the future.

7.3 Scientific relevance

The scientific relevance of this research is illustrated in three aspects.

First, it explores the trend of the evolvement of the construction robotics research. Robotics has been applied in the construction industry for several decades. With such a long span of time, it could be imagined that the interests of the related research might have shifted from the original ones. However, very few research has tried to reveal the shift. By systematic reviewing the paper from ISARC Symposium, this research tries to conclude the recent trend in this field, revealing the hot point in construction robotics research.

Second, it reveals a full picture of the currently available construction robotic technologies (in the two selected fields). It could be observed that since the 1990s, technologies in the construction robotics has expanded from the 'traditional' ones, which are mainly about mechanism and engineering, to a wider spectrum, including virtual reality, GPS, RFID, etc. With the development of informationalization since the first decade of the 21st century, many technologies related to information process and management have involved in industrial sectors, contributing to the 'fourth industrial revolution' (Industry 4.0). This is also happening in the construction industry. By far, very few overview of these 'new' technologies' application in construction robotics is available. This research tries to summarize the currently available robotic technologies and the pattern of their application in construction.

Third, this research tries to provide a perspective to explore the future development of construction-robotic technologies. The landscape of the construction technologies is dynamic, and evolves at an increasingly fast rate, being affected by many uncertain factors. In this research, scenario planning is employed as a tool to manage these uncertainties. Then based on the most relevant uncertainties, a set of scenarios for the future world are developed to cover the possible future of the technical innovations in the construction industry. It is not a prediction or forecast of the future, which aims at a most probable single landscape, but a spectrum covering the possible landscapes. This method provides an all-around perspective to observe the future development of construction robotics technologies.

7.4 Societal relevance

The construction industry is one of the major economic sectors in the Netherlands. However, similar to its counterparts in other countries, the Dutch construction industry suffers from a relatively low efficiency and productivity. Robotics as a solution has been introduced into this industry, hoping to enhance the efficiency. Unfortunately, by far not a greate deal of progress has been made. This research tries to help the industry to improve its robotics level by sweeping some of the obstacles in adopting new robotic technologies in construction activities. It summarizes the emerging technologies in construction and infers the possible future landscapes in construction robotics technologies. This study could assist the related practitioners' decision-making processes in adopting and investing in robotic technologies, thus help the construction industry to improve its efficiency, saving a significant amount of sources.

7.5 Utilisation potential

The utilization potential of this research also has a three-fold meaning.

First, it could be used as a reference for the practitioners in the construction industry to figure out technologies that could help to fix the problem they are facing. As mentioned previously, the technologies that could be used in construction right now are various, which is probably confusing picture for the practitioners.

Second, this research reveals the possible directions of the emerging technologies' future development in different scenarios, providing a clue for the research and development activities in construction. The technologies that are likely to boom in the future deserve more attention. The actors in R&D activities in the construction industry could adjust their policy according to the evolvement of the scenarios, maximizing the effectiveness of their R&D investment.

Third, by comparing the development of the emerging technologies' development in the three scenarios, the overlap of the scenarios is figured out, as the most solid field to invest for the contractors. Investment in the technologies located in this field, including the equipment, worker training, software purchase, will be most worthy, playing a role in all the three scenarios, with the lowest risk of waste.

7.6 Validity of the results

This research consists of two parts: the state of the arts, and the state of the future of the construction robotics technologies. The issue of validity mainly exists in the second part, which is the future study.The future study is based on scenario planning, which requires involvements of experts in the construction industry. The selection of respondents affects the validity of the results.

Experts-involving research process

The experts are interviewed to identify the major factors that may affect the future development of the emerging technologies, and then they are required to evaluate these factors. According to their evaluation, two key factors with high impacts and low predictability are selected to establish a scenario matrix. Thus, a set of scenarios is constructed. By inferring the evolvements of the emerging technologies in different scenarios, the future landscapes of construction robotics could be depicted.

Effects of limited number of participants and countermeasures

However, in the conduction phase of the research, it turns out that it is not easy to find enough number of experts who are willing to take part in the research. Mostly, invitations do not get any response or the replies refusing the requirement. Finally, six experts accepted the invitation and joined in the research (for details see Appendix C). The limited number of interviewees may damage the validity of the results in two aspects.

First, limited interviewees mean limited information that could be collected. To deal with that, literature and available publications are employed to reduce the possible omissions. For instance, in the factor identifying phase for scenario planning, the participating interviewees are expected to provide as many factors as possible. Considering the limited number of interviewees, some desktop research was done beforehand, to investigate the factors that have been mentioned in existing literature, and they were classified with the PESTLE framework, as a reference in the interviewees. Another example is that in the future development of the currently available technologies, blog posts about the technologies' future application were used as supplements.

Second, in the quantitative assessment of the factors, the small sample size affect the results. The assessment was done via an online survey. In the survey, the participating experts are required to evaluate two parameters of each factor: the impact and the predictability, using a seven-point Likert scale, and the average of the scores are taken as the final scores. To make the results are as valid as possible, in the process of calculating final score of each parameter, not only the average score is calculated, but also the deviation. A lower deviation reveals that the experts have a higher level of agreement on the specific issue. For the issues with high deviation, further analyses would be conducted to make sure that the results are proper. Fortunately, the deviations of the results for all the factors are acceptable, which means the experts have relatively close opinions on impacts and predictabilities of these factors, thus the results are to some extent solid.

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Appendices

Appendix A	Technologies in construction robotics
Appendix B	The Method for Tasks Selection
Appendix C	Details of interviews
Appendix D	Questionnaire for factors assessment
Appendix E	Summary of the currently available technologies
Appendix F	Possible future evolvement of the currently available technologies

Appendix A Technologies in construction robotics

Internet of Things (IoT)

IoT aims to integrate the virtual models and physical construction to facilitate the bi-directional coordination between them (Akanmu & Anumba, 2015). IoT is a combination of sensors (for instance RFID and intelligent cameras), other communication devices, cloud applications, ERP integration and business intelligence technology (Whitelight Group, 2014). The sensors are connected to the internet, and the performance data of equipment could be sent in real time to engineers to be analyzed. Thereby, predictive maintenance could replace reactive maintenance (equipment works until failure and then get repaired) to enhance efficiency in construction (Thompson, 2015). IoT could save a considerable amount of cost ($160 to 930 million annually) on construction sites (Manyika et al., 2015).

Additive Manufacturing (AM)

Additive Manufacturing is also known as 3d printing and contour crafting in construction. It enables complex construction components to be produced by automating manufacturing without extra labor costs. Nowadays, AM technology is mature enough (Team, 2016) and 3D printed homes are being offered for the commercial use (Winsum, n.d.), a widespread application of this technology in construction is being expected for 2020 onwards (Baynes & Steele, 2015).

Modularization and Prefabrication(M&P)

Modularization is known as prefabrication in construction. It has already been widely adopted in construction companies (McGraw-Hill Construction, 2011), because of the great benefits it provides to enhance quality and safety while reducing waste and costs(Hong, Shen, Mao, Li, & Li, 2016).

Automation and Robot (A&R)

A&R mainly covers the hard robotics technologies. It has been used in construction for relatively long time in construction, e.g. automatic robots for steel beam assembly (Chu et al., 2013), commercial bricklaying robots (Fastbrick Robotics, n.d.), robots can sort through construction waste to seek for recyclable materials, removing asbestos or finish concrete floors (KFMR, n.d.), etc.

Human-Computer/Robot-Interaction (HCI/HRI)

HCI focuses on the communication between human and intelligent equipment, for example the influencing factors for successful implementation of mobile computing (Son, Park, Kim, & Chou, 2012), or the framework for identifying and understanding the factors of individual acceptance and use of ICT (Zakaria, Ismail, & Yusof, 2014). In many cases, the way humans interact with an instrument (e.g. robots, computers, intelligent equipment), is considered as one of the most predominant factors in successfully implementing a solution on a construction site (Bruemmer, 2016).

Laser Scanning and Prototyping (L&P)

Laser scanning is also known as Point Cloud in the construction industry. By scanning the built environment it retrieves the coordinates of a series of points in the space to establish a virtual environment in short time. The outcome of could be used in inspection to assess the built quality, monitoring the construction safety onsite, making as-built drawings, etc.

Virtual Reality/Augmented Reality (VR/AR)

VR aims to create a risk-free virtual environment for learning and training in construction (King Chun, Li, & Skitmore, 2012). Also, the derived technology Augmented Reality (AR) is being used for supporting defect management in assembly (Park, Lee, Kwon, & Wang, 2013), or real-time communication on-site (Wang et al., 2013). In practice, the use of VR is still not widespread and under developing. Besides, VR and its derived technologies are always applied together with mobile devices or wearable computing to enhance safety on construction sites (Jones, 2014). They can also be employed to enable remote support and manipulate (H.-K. Wu, Lee, Chang, & Liang, 2013).

Building Information Modeling (BIM)

BIM is the technology that is widely applied currently. Many countries have made or are going to make BIM mandatory for main projects (Hardin & McCool, 2015). In essence, BIM is an innovative technology to virtually design and manage construction projects by simulating a virtual model of a building. By providing relevant information like project schedule, cost estimates, material inventories as well as technical information about the building elements such like geometry and spatial relationships, the building information model offers the opportunity for all project members to collaborate in an efficient way (Popov, Juocevicius, Migilinskas, Ustinovichius, & Mikalauskas, 2010).

Simulation and Algorithm (S&A)

S&A is a method using computing technologies to simulate some complicated process in a computer, for instance, the work schedule, site planning, logistics organization, energy consumption, etc., to optimize the real process and avoid possible waste.

Cloud Computing (CC)

Cloud Computing provides integrated services with the opportunity to be accessed via the Internet, for instance, cross-company collaboration on a construction site. It is used to enable all project participants to access information from any communication device with Internet and therefore creates a 'single source' for the whole project team, based on a file-sharing collaboration platform in real time (B. Kumar, 2010).

Big Data (BD)

Big Data helps to collect the right data from all data-generating devices or agents like BIM models, embedded sensors, computers, machines or people and to make them accessible to project participants (McMalcolm, 2015). For instance, the analysis of historical big data (for instance weather, traffic or business activities) makes it possible to identify patterns and probabilities of construction risks for performance improvements in future projects or enhanced decision-making (Burger, 2016). Big Data has not been widely applied in construction yet (Oesterreich & Teuteberg, 2016).

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Appendix B. The Method for Tasks Selection

Due to the time constraint of the master graduation research, it is less likely to examine the technical innovation across the whole construction sector. It will be advisable to select several tasks to study in detail. As mentioned in the report, the construction robotics is expanding its concern from the first type of works to the second, therefore, to represent the current context in construction robotics, two tasks will be selected, one from each type.

From 2012 to 2016, the ISARC (International Symposium on Automation and Robotics in Construction) proceedings include 572 papers in related to construction robotics, among which 255 are about the application of technologies in particular construction tasks. By reviewing these papers, the tasks they concern could be concluded as Table A.1

Table B.1 Identified construction tasks concerned by ISARC papers

Identified tasks in the onsite construction work	
Cluster	Tasks
First type: directly related to the physical production	Earthwork
	Reinforcement
	Paving
	Concrete distribution
	Concrete finishing
	Welding
	Coating
	Assembly
	Interior finishing
	Masonry
Second type: related to the construction process	Surveying and monitoring
	Logistics
	Site planning and management
	Safety
	Quality control
	Process management

Criteria for task selection and assessments

To select two tasks from this list, four criteria are taken into consideration, which are:

- Possibility to be executed onsite;
- Concerns of academia;
- Technology involvement;
- Connection to the practice.

These criteria will be discussed and used to assess the tasks in the following part.

1. *Possibility to be executed on site*

   This research focuses on the onsite construction works. Therefore, the tasks that are more likely to be done onsite deserve priorities in the selection. The assessment is difficult to be quantified and mainly depends on the qualitative analysis.

In the Netherlands, the industrialization started quite early, and the percentage of the industrialized residential building reached 40% in 1996, in Europe only next to Denmark (43%) then (Jaillon & Poon, 2009). Most of these buildings are realized by prefabricated concrete components. The prefabrication has helped to reduce construction cost and period, enhance building quality in the last few decades. Although there are still many projects, especially those unique public buildings, requires situ concrete work, the onsite concrete work is losing its share in the whole sector worldwide (Elliott & Jolly, 2013). With this background, the related tasks in the identified list, including reinforcement, concrete distribution, concrete finishing, are mostly transferred to offsite work. Onsite welding, which was used to formulate the mesh in situ concrete, is also affected by this trend and the prefabrication of steel substructures.

With the application of curtain wall system, the onsite coating work around the world has declined. However, in Europe, because of a large amount of building heritage, coating work is still required for the repairs, although the amount is quite limited. Besides, sometimes in steel structure building, fireproof coating works are still done onsite (Caldic, n.d.). Interior finishing works are also partly done offsite, especially in the modularized construction, but because of the non-standard interior environment, it is difficult to move all the finishing works offsite. Masonry works are less used recently in new projects, because the prefabricated components, as more economical alternatives for masonry walls, are replacing its role; currently, masonry works onsite are mainly used for decorative exterior or interior walls, and repairs of the historic buildings (Fatiguso, De Fino, Scioti, & Rubino, 2015).

The remaining three tasks in the first type of works, earthworks, paving, and assembly, are less likely to be done offsite.

The second type of works mainly focuses on the process of the construction. Therefore, most of them are executed on site, except 'site planning and management', and 'process management'.

According to the previous analysis, the construction tasks could be classified into four groups:

- 1: could be done completely offsite;
- 2: could be moved away from construction sites to larger extent;
- 3: could be moved away from construction sites to a smaller extent;
- 4: could be done only onsite.

In the assessment of this criterion, the tasks belonging to the four groups get scores of 25, 50, 75 and 100 respectively. The scores of the identified tasks are illustrated in Table B.2.

Table B.2 The scores of the possibility to be done onsite

Cluster	Tasks	Group	Score
First type: directly related to the physical production	Earthwork	4	100
	Reinforcement	2	50
	Paving	4	100
	Concrete distribution	2	50
	Concrete finishing	2	50
	Welding	3	75
	Coating	3	75
	Assembly	4	100
	Interior finishing	3	75

	Masonry	3	75
Second type: related to the construction process	Surveying and monitoring	4	100
	Logistics	4	100
	Site planning and management	1	25
	Safety	4	100
	Quality control	4	100
	Process management	1	25

2. *Concern of academia*

More concern from the academic circle represents the hot points in the field. Focusing on these hot points will be more scientifically and practically relevant.

The indicator for this criterion is the number of ISARC papers that concern the particular tasks in the recent five years. The following table (Table B.3) shows the number of papers focusing on each task. The task with most papers focusing get a score of 100; if no paper concerns, the score will be 0. The scores for other tasks are determined by linear interpolation.

Table B.3 The numbers of the papers focusing on different tasks and their scores of the concern of academia

Numbers of ISARC papers focusing on different tasks			
Cluster	Tasks	Number	Score
First type: directly related to the physical production	Earthwork	27	63
	Reinforcement	4	9
	Paving	1	2
	Concrete distribution	0	0
	Concrete finishing	5	12
	Welding	0	0
	Coating	5	12
	Assembly	18	42
	Interior finishing	4	9
	Masonry	2	5
Second type: related to the construction process	Surveying and monitoring	26	60
	Logistics	24	56
	Site planning and management	36	84
	Safety	43	100
	Quality control	13	30
	Process management	37	86

3. *Technologies involvement*

The targets of this research are to figure out the currently used technologies and the possible future of the technologies' application in the selected tasks. For different tasks, different types of technologies are applied. Tasks involving more technologies have higher priorities to be studied.

The ISARC paper in recent five years will be examined and classified according to their focusing tasks and technologies, to see which tasks cover a boarder spectrum from the technical perspective. The number of identified key technologies involved in each task will be calculated. The task with most technologies involved gets 100, and the scores for other tasks will be determined by linear interpolation. See Table A.4 and A.5.

Table B.4 The numbers of technologies that involved in different tasks

	IoT	A&R	M&P	AM	HCI	S&A	BIM	VR/AR	CC	BD	L&P	other	total
Earthwork	3	7	0	0	0	3	3	0	0	0	1	9	27
Reinforcement	0	1	0	0	0	1	2	0	0	0	0	0	4
Paving	0	0	0	0	0	0	0	0	0	0	0	1	1
Concrete distribution	0	0	0	0	0	0	0	0	0	0	0	0	0
Concrete finishing	0	1	0	1	0	2	0	0	0	0	0	1	5
Welding	0	0	0	0	0	0	0	0	0	0	0	0	0
Coating	0	5	0	0	0	0	0	0	0	0	0	0	5
Assembly	1	6	1	0	0	3	1	1	0	0	2	3	18
Interior finishing	2	1	0	0	0	0	0	0	0	0	1	0	4
Masonry	0	1	0	0	0	0	1	0	0	0	0	0	2
Surveying and monitoring	9	4	0	0	0	2	2	0	1	0	3	4	26
Logistics	2	4	0	0	0	11	2	0	0	0	1	4	24
Site planning and management	6	1	0	0	0	10	5	1	0	0	5	6	36
Safety	7	4	0	0	0	7	2	3	1	3	1	15	43
Quality control	0	2	0	0	0	0	1	0	0	0	6	4	13
process management	3	2	0	0	1	9	4	1	2	0	1	10	37
other	1	6	0	2	2	1	5	3	1	0	2	0	26
total	34	45	1	3	3	49	28	9	5	3	23	57	271

Note: * The number with orange background represent the number of papers involved with the particular technologies in particular tasks; while the number in the last column means the number of types of identified key technologies applied in the particular tasks.

Table B.5 The assessment of the technologies diversities of different tasks

Numbers of identified technologies involved in different tasks			
Cluster	Tasks	Number	Score
First type: directly related to the physical production	Earthwork	7	70
	Reinforcement	3	30
	Paving	0	0
	Concrete distribution	0	0
	Concrete finishing	3	30
	Welding	0	0
	Coating	1	10
	Assembly	7	70
	Interior finishing	3	30
	Masonry	1	10
Second type: related to the construction process	Surveying and monitoring	7	70
	Logistics	5	50
	Site planning and management	8	80
	Safety	8	80
	Quality control	3	30
	Process management	10	100

4. *Connection to the construction practice*

This research mainly focuses the construction practice in the Netherlands; therefore, the selected tasks should be more closely attached to the Dutch construction industry, so that it will be easier to find qualified experts as interviewees for the empirical part of this research.

To evaluate the relationship between particular tasks and the construction practice, the numbers of patents related to particular tasks in recent years will be taken as indicators. It is reasonable to assume that more patents in a particular task indicate that this task is an active field in practice. The database from European

Patent Office is used, and the date range is from 2011 to 2016.

Another problem emerges when conducting this method. The numbers of patents from the Netherlands are quite limited and therefore the sample is too small. Therefore, the corresponding numbers from the US are examined (also using the same database), to make a comparison with the Dutch numbers. The result is shown in Table B.6.

Table B.6. The numbers of patent related to each task in the Netherlands and US from 2011 to 2016

Numbers of patent related to different tasks				
Cluster	Tasks	Keywords	NL	US
First type: directly related to the physical production	Earthwork	earthwork OR excavation	2	393
	Reinforcement	(construction OR building) AND (reinforcement OR rebar)	3	288
	Paving	paving	2	391
	Concrete distribution	concrete distribution	0	44
	Concrete finishing	concrete finishing	0	54
	Welding	(construction OR building) AND Welding	1	136
	Coating	(coating OR spraying) AND (construction OR building)	4	285
	Assembly	(construction OR building) AND assembly	6	2013
	Interior finishing	interior finishing	0	52
	Masonry	masonry	2	362
Second type: related to the construction process	Surveying and monitoring	(surveying OR monitoring) AND (construction OR building)	0	522
	Logistics	(construction OR building) AND Logistics	0	12
	Site planning and management	(construction OR building) AND site planning	0	6
	Safety	(construction OR building) AND safety	4	407
	Quality control	(construction OR building) AND quality control	1	306
	Process management	(construction OR building) AND process management	0	67

It turns out that the two sets of numbers match each other quite well, see Figure A.1. Assembly and onsite safety issue are most active practice fields in the first and second types of works respectively. The numbers of the Dutch patents in different tasks are used to assign the scores. The scores are concluded in Table A.7.

Figure B.1. The numbers of patent related to each task in the Netherlands and US from 2011 to 2016

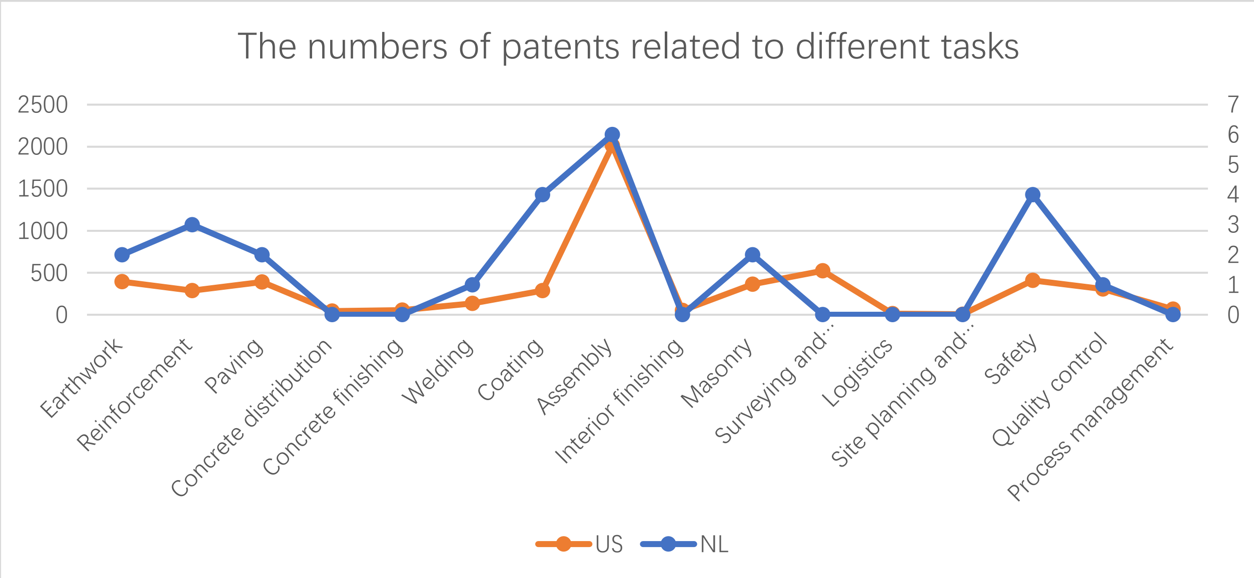

Table B.7. The scores of the different tasks in practice attachment

Numbers of Dutch patents involved in different tasks			
Cluster	Tasks	Patents Number	Score
First type: directly related to the physical production	Earthwork	2	33
	Reinforcement	3	50
	Paving	2	33
	Concrete distribution	0	0
	Concrete finishing	0	0
	Welding	1	17
	Coating	4	67
	Assembly	6	100
	Interior finishing	0	0
	Masonry	2	33
Second type: related to the construction process	Surveying and monitoring	0	0
	Logistics	0	0
	Site planning and management	0	0
	Safety	4	67
	Quality control	1	17
	Process management	0	0

The comprehensive score and conclusion

Considering the four criteria, each of them takes a weighing factor of 25%, the final scores are concluded in Table A.8. **Assembly** and onsite **safety** issue get the highest point in the first and second types of works respectively. Therefore, these two tasks will be picked out and studied in detail.

Table B.8. The final score of the different tasks

Final scores of different tasks						
Cluster	Tasks	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Total score
First type	Earthwork	100	63	70	33	67
	Reinforcement	50	9	30	50	35
	Paving	100	2	0	33	34
	Concrete distribution	50	0	0	0	13
	Concrete finishing	50	12	30	0	23
	Welding	75	0	0	17	23
	Coating	75	12	10	67	41
	Assembly	100	42	70	100	78
	Interior finishing	75	9	30	0	29
	Masonry	75	5	10	33	31
Second type	Surveying and monitoring	100	60	70	0	58
	Logistics	100	56	50	0	52
	Site planning and management	25	84	80	0	47
	Safety	100	100	80	67	87
	Quality control	100	30	30	17	44
	Process management	25	86	100	0	53

Note: C1: Possibility to be done onsite; C2: Concerns of academia; C3: Technology involvement; C4: Attachment to practice.

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Appendix C Details of interviews

In the research eight expert interviews are conducted, with six experts involved in, four from the academia and two from practice., their information is listed in Table C.1.

Table C.1 Background of the interviewees

Interviewee	Background	Organization
Bauke de Vries	Academia	Professor, Urban system & Real Estate, Department of the Built Environment, Eindhoven University of Technology
Aant van der Zee	Academia	Assistant Professor, Urban system & Real Estate, Department of the Built Environment, Eindhoven University of Technology
Frans van Gassel	Academia	Retired Assistant Professor, Eindhoven University of Technology
Alex Liu Cheng	Academia	Ph.D. researcher, Department of Hyperbody, BK faculty, Delft
Michel Meijer	Practice	Partner manager, Supply Chain Management, Dura Vermeer
Michiel Bottema	Practice	Manager BIM, Heijmans

The eight interviewees are classified into three sets, with different purposes, as shown in Table C.2.

Table C.2 Categories of the interviews

Cluster	Number	Interviewee	Purpose
1	1	Bauke de Vries	To identify the factors for scenario planning.
	2	Aant van der Zee	
	3	Alex Liu Cheng	
	4	Frans van Gassel	
2	5	Frans van Gassel	To get knowledge about the current application of the identified technologies in the Netherlands, as well as drivers and barriers of their application.
	6	Michel Meijer	
3	7	Aant van der Zee	To discuss the established scenarios with experts, generating inputs for the scenario narratives.
	8	Michiel Bottema	

Set 1 Interviews for factors identification

This set of interviews are not strictly structured, but more like casually talks, aims to figure out the factors that may affect the future development of the construction robotic technologies. The talks are organized with a PESTLE (Political, Economic, Social, Technical, Legal, Environmental) framework. A list of the pre-identified factors is shown and explained to the interviewees, and they are required to comment the factors that they are interested in.

Table C.3. The pre-identified factors for the interviews

Political	Supporting policy;
Economic	*labour cost;* *economic prospect;*
Societal	*demographic evolvement;* *availability of the practiced craftsman;* *young people's preference in career;* *Globalization;* *aesthetic orientation;*
Technological	*Artificial intelligent;* *ICT technologies;*
Legal	*Related regulations;*
Environmental	*Requirements for reducing carbon emission;* *Energy supply and cost;*

Interview 1

Interviewee: Bauke de Vries

Time: 11:30-12:00, March 29th, 2017

Place: Vertigo 9th floor, TU Eindhoven

L: (The introduction part is left out, including the objective and method of the research). As I have mentioned in the introduction part, the future study of the research depends on a scenario planning method. The first step of scenario planning is to figure out and evaluate the factors. I have preliminarily identified some possible factors. Do you have any comments on these factors?

V: Okay… what do you mean by 'young people's preference in career'?

L: I mean young men's interests in career will affect the availability of labors in the construction industry, and thus the technologies may evolve to the direction of labor-saving…

V: Well most what will affect young people's decisions are their expectation at the time for successful career and that depends on the economy. Sometimes the economy is not good, especially the construction market is very sensitive to that, then it could be observed in the Netherlands that even school children already will not choose to study architecture because they are worried that when they get the diploma they will not find a job. So, we can see the influence going down, and once the economy goes up, I've seen that over the past years, now, since one or two years, the economy is going up, we get extra more students.

L: So, actually, this factor could go with the economy fluctuation. But, as the time horizon of the future study is 2030 in this research, while the economy fluctuates on a one to two years' basis…

V: That's a bit too short. I think economy fluctuations typically take longer time. I'm not an economic expert, but it always goes in parallel with the economic crisis. Then you are talking about longer time, that will be very difficult because you have no idea, no clue. this is one of the variables I think is almost impossible to predict. So maybe the economy fluctuation is one of the 'wild cards' that is difficult to manage and is not proper to be used as a factor for your scenario planning.

L: Yes, I will consider that.

V: And demographic evolvement. I think it is a political issue, meaning what do you do with the workers lost their jobs because of robotics? we can say it is happening everywhere. If you see the car manufacturing, which is almost totally robotic, partly manually done, but still has removed a lot of traditional labor jobs in that area. In our field, the construction industry, this process evolves much slower, but it does happen, and also, we can say in the Netherlands, a lot of people lose their jobs especially in administration because the computers take over the simple jobs, for instance, budget management. Jobs we did in the past to manage the budgets are not done by computer systems. Some companies, for example, SAP, sell such kind of software, to almost everyone to do financial management of factories, universities, again, people lose their jobs.

L: Yes, that is a factor.

V: Then 'aesthetic orientation'…

L: Ah that, I think people's preference for the appearance of buildings will affect the robotic technologies, in the last few years, a trend is that more and more people are interested in the non-standard buildings, so that some technologies, for example, the prefabrication, will be less used than before…

V: Well this is an issue about standardization and massive production. The nice thing here is due to robotics, due to automation of construction process, things are changing. There is a famous Ford quota that we can construct any car as long as you expect. Today they can make huge diversities of cars, but still it is modular, so in the past we always thought that the automation always mean, let's say, less diversity, but today you see, it creates more diversity. It is also reflected in the construction industry. In the past, the different components in a building is an issue because it means the building will be very expensive, the factory has to make every single component, but for robotics, it does not matter. It takes other input and construct it. I think it does not so much depend on how it is fabricated because technically it is not a big problem anymore.

Finally, I would like to make a supplement. The business model in the construction industry also affects the robotics. There are literature comparing the construction industry and manufacturing industry, the most frequently mentioned is that construction industry is very fragmented. Car industry, maybe you know, there are 10 or maybe 20 famous producers in the world, but the construction, maybe there are a few hundred within the Netherlands, maybe working with one or two people. You can see over the history that the car manufacturing organized themselves and the whole supply chain very effectively, because they produce their products on a daily basis, whereas in the construction industry, we always get an assignment to make a building, we do it and then we move to the next one, with different team, new job, new assignment, new project, completely different from the previous one. Every time you work with a different team, that is the main difference. If you look at the company of Ford, they have the complete control of the whole process, from the start of the idea, until the car is taken into part or demolished. So, what if construction works in a more self-organized way? That may bring great difference to the industry.

L: Okay, thanks for your time.

Interview 2

Interviewee: Aant van der Zee

Time: 13:00-14:00, March 29th, 2017

Place: Vertigo 9th floor, TU Eindhoven

(The introduction part, including the objective and method of the research).

L: As I have mentioned in the introduction, the future study part will employe a scenario planning-based mehod. The first step is to identify some factors that may affect the future development of the construction robotics te technologies. I have preliminarily identified some possible ones. Do you have any comments on these factors?

Z: Well, I think you should take into consideration one important factor that people's response to the robotic technologies, because construction robotics may take over jobs from human workers.

L: Do you mean that the government may have some regulation laws to limit the robotics to protect people's jobs? I categorized it into the legal part.

Z: No, I don't think the government has ideas about this, but the labor unions have more impact. They could say, okay, robotics cuts position for men to work, the robots will take jobs over. I never heard the governments are talking about negatively automation. The government, I think, more will help to make it happen, the automation, but not to prevent it. But the labor unions, they will say, this is not correct.

L: I can understand that they affect the use of robotics, but how can they affect the direction of the technologies?

Z: Let's say, if the big companies use a lot of robotics, they need fewer people; if they face the pressure (from the labor union), there must be some way to keep people inside the firm. So they may prefer to adopt the technologies that do not reduce the number of workers.

L: You mean they will generate some pressure or obstacles for the development of construction of robotics.

Z: Yes, they place obstacles with the CEO, meetings, because of the loss of jobs. But this is a trend that you cannot stop. It happens, if you think about the driverless cars, it is going to take over jobs from drivers, you cannot stop that but only to adapt to it.

By the way, you mentioned the policy's affect, also as a political factor. Personally, I think it is very rare that the government will directly support a specific technology or a specific direction of the technologies' development; they may indirectly affect that, if you look at let's say safety management, the government says you have enhanced the safety performance, then maybe the companies will look for some ways, including wearing a hard hat on, glasses, whatever. That's an example.

L: So, the government may affect the development direction of robotic technologies indirectly by making some rules or regulations.

Z: Yes. Regulations. But the to predict the regulation's development in the future is hard. It depends on the circumstances, social, economic changes, so, basically impossible.

And another problem may affect the robotics in construction is the way how the industry works. The way we manage it now is that we have to bid to get a job. The lowest bidding gets a job. So, the contractors in a project cannot say so many percents are for development (not enough money for research and development activities).

They are always looking for the cheapest way to make it happen (to build the building). that is the biggest reason that the companies don't development techniques. A lot of companies, they don't do research, they don't have money or department for research.

L: not enough investment in research.

Z: Yes. And I think the whole system of bidding of our projects, that the lowest bidder gets the job. So, they cannot say that this ten percent is for research, no, because if we give the ten percent, we may probably lose the job. I think that is also one of the biggest reasons. Projects are completely different, cars are the same, the shells, the doors are all the same, you can give them different colors, but nothing is really changed. Every five years, they have a new type and they make the whole streamline changed to adapt the new models. But in construction, everything is different.

L: But we can see that in the construction industry some progress has been achieved in standardization, for instance, the prefabrication and modularization in the construction industry. The designers tried to keep the components standard so that they can be produced in a way similar to the cars.

Z: Yes, the components are similar, but still each project is different, because of the soil, the regulation, everything. The engineers have to cope with it. they have to adapt to different regulations, and different sites, climates, whatever. So still each project is very different. You cannot copy from another one. But for a car, you can copy. Similarly, for modularized buildings, the units could be the same. The wall the windows are all the same. But that is not the complete building. The skeleton, the coloum, floors, the whole structure, need to be calculated for each project. If you give the commission to build a house, it won't be the same as my house. We can standardize, or modularize components of houses, more the LEGO box, but the outlook will be different. People like to pinpoint their own house, so if you have ten in a row, everyone would like to say, that house with the yellow door is my house, not the sixth on the left is my house.

L: So, people are still pursuing personalities.

Z: Yes. So, I think it is very hard to completely standardize the buildings.

I want to say another thing that important for robotics. conservativeness also matters. In exploration of technologies, you have to try to invest in some end to see if it is possible if it turns out it doesn't, then we know, okay we will go in a different way. I think many companies don't think this way. They say we wait, we wait and see what's happening. Then they are too late. Because people who have invested in it have great advantages, they get the jobs and projects, they gain more knowledge about the using. For instance, there are now some groups making a jump in 3D printing, by making the jump they will gain more knowledge, and left behind those who didn't. I know there are a few companies who made the jump and I know one of them who was in the beginning eager to make the jump and somewhere make the process, in the management process, some others don't, they say there is a lot of things we can do, but not 3D printing, so they are left behind. But that also depends on the company's scale, as I just said, the working way we use to get a job in construction now is to bid, and the lowest price helps you to get works to do. So, for the small companies, they don't have enough money.

And I think that's all that I can give.

L: Okay. Thanks for your time!

Interview 3

Interviewee: Alex Liu Cheng

Time: -

Place: -

(*Alex Liu has been out of the Netherlands since the end of March. This is actually not a script of an interview, but he explained several factors that he thinks important in an email. The text is translated from Chinese.*)

My research focuses on the technical sector, so I mainly talk about this part, including two main factors: 3D printing (additive manufacturing) and artificial intelligence.

First, maybe you should consider 3D printing as a factor. 3D printing helps to solve the problem of uniqueness of individual projects in construction. Projects are still different, but with 3D printing technology, their differences do not depend on different crafts, but being dealt by 3D printers, with assistances of digital design documents. Construction robotics to large extent depends on automatic equipment onsite, therefore, fewer crafts needed onsite means fewer types of equipment, and the robotic technologies will be less diverse. So, although 3d printing has not shown its influence on the construction robotics technologies, it could be expected that it will probably matter in the future.

For now, the biggest problem I think in 3D printing, is the issue of dimension. Similar to 2D printers, the 3D printers' robotic arm should reach a larger range than the objects printed. But generally, even the simple buildings are larger than an ordinary 3D printer. Three solutions are available for this problem. The first is to build larger printers, then bigger structures could be printed (see http://d-shape.com/). The flaws of using larger printers are that the printing speed and accuracy will be affected negatively, also big printers are relatively expensive. The second solution is to decompose the building into different sections, then to print each section separately, and transport the sections onto the construction site to assemble them into a whole building (see http://www.softkilldesign.com/). This method requires much more assemble work on construction site. Finally, the solution I personally think most promising is to use swarm printers, which consists of multiple printing robots, to work together to print large objects. The printers could even be combined with drones, to work more flexibly. The individual 3D printers are much less complicated, therefore, cheaper to purchase and maintain. Also, this method of group working fits the development of artificial intelligence.

The second factor I suggest is the artificial intelligence. Robotics in construction is limited by the lack of self-learning capability. Everything robots do rely on the program embedded in them, thus, they can hardly deal with the dynamic and unstructured onsite environments. If the real AI could be realized in your time horizon for the research (See https://en.wikipedia.org/wiki/Artificial_general_intelligence), with its control, robots will be able to manage most of the work on construction sites automatically. Much fewer workers are needed to work onsite, and this change will affect the construction industry and the robotic technology profoundly. For example, the original target of construction robotics is to replace human labors in practice; however, when the building process is totally, or closely totally taken over by AIs and robots, with hardly any human labors, what will be the new target and to what direction will the construction robotics move? A possible future development in construction robotics related to AI's application maybe the swarm robots. Similar to the swarm printers I mentioned previously, swarm robots refer to a group of standardized, versatile robots, which are able to execute different types of tasks, organized by AI networks. They are smaller, and much more flexible.

Interview 4

Interviewee: Frans van Gassal

Time: 15:00-15:20, March 29th, 2017

Place: Vertigo 7th floor, TU Eindhoven

L: (The introduction part, including the objective and method of the research)

As I said in the introduction, the future study part will be started with scenario-planning. The first step is to identify the factors that may affect the futur development of the construction robotics te technologies. I have figured some possible ones. Do you have any comments on these factors?

G: In the economic part, maybe the wages also matters. At this moment, the wages in the Netherlands is so high, so there coming a lot of people from Poland, cheaper. If you go to the construction sites, you will probably see a lot of non-Dutch speakers. Some of them are from Poland, Poland is within the EU, so Polish workers come into the Dutch construction industry. they work harder the Dutch. But, after five or six years, the income of Poland will be higher, and less polish labors will come to the western part of Europe. So, you have to mechanize, to robotize the construction. So that will be a motivation.

L: So, the high labor cost motivates the use of construction robotics.

G: You said 'young people's preference in career', that means?

L: Ah, by that, I mean, as I know, high school students in the Netherlands will receive an advice about which types of the schools they are going to apply, so they will have a plan for their future career. So, I guess young men's interests in career may affect the labors supply in the construction industry?

G: Young men are not so interesting in blue collar work, because of the wage is lower than the white collar.

L: So, I'm thinking, maybe I can merge this item with the issue of wages level, which you just mentioned, into a new item, 'availability of labors'. Because the high wage level in the construction also indicates that the labor is not that easily available for the Dutch construction industry.

G: Yes, I think you can. This is also a political issue.

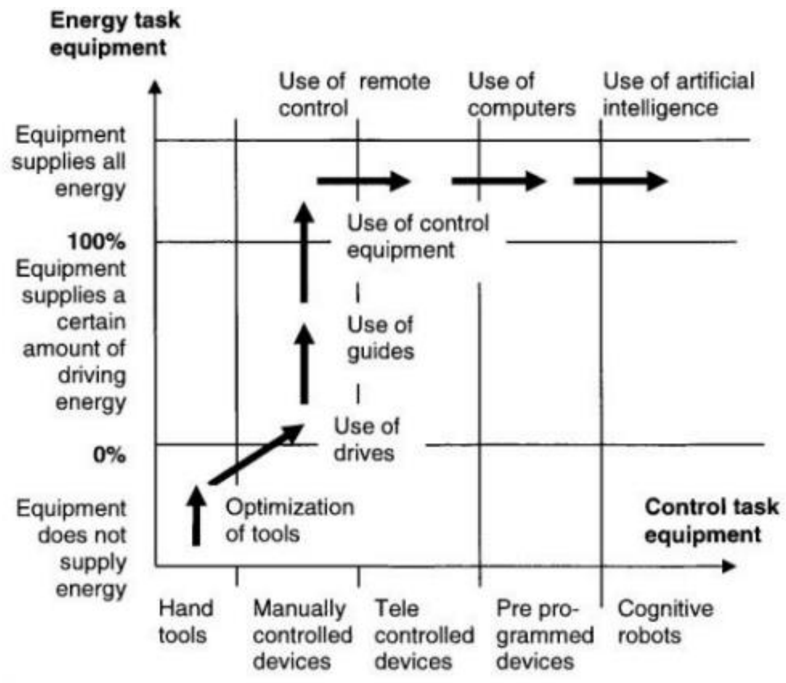
L: Then I guess actually the demographic evolvement can also be merged. Because the demographic structure also decides whether you can find enough labors.

G: No. I understand demographic from another point of view. In the Randstad area, the population is growing. In these areas, demands for buildings are stimulated. But in the depressing areas, there are very rare new construction activities. No new roads, no new houses. The development of robotics mainly depends on the new development of areas, where there are a lot of works to do; it is easier to use robotics in the construction of new buildings than in refurbishment. Like, in the Netherlands, the energy consumption had gone through a big transition to using gas, so in the 20th century, millions of houses needed to be refurbishment to add gas facilities; that was a lot of works, created many new jobs, but not a chance for robotics, the working environment of existing stocks is very complex. It is difficult. So, in booming area, you have more chance to use robotics, but in old areas, there are more renovation works, that will be done by manual works. The chance for using construction robotics is not much.

L: Yes, that is a new perspective for me.

G: And I agree with you about the artificial intelligence. Let me show you my work. I think construction technologies develop along the way like shown in this picture (Figure C.1) (http://www.slimmerontwerpen.nl/). In this work, I determined there are two dimensions in the development of construction robotic technologies: the level of human's intervention in thinking works and physical works. At the beginning stage, the construction robotics developed to save energy for human workers, and now they basically realize that; but the thinking works still need, or partly need to be done by human beings. In the future, the completely cognitive robots may appear, and that depend on the development of artificial intelligence.

Figure C.1. Mechanization phases by construction works (source: Maas, G. J., & van Gassel, F. J., 2011)



L: This is inspiring.

G: Environmental, yes that's important. Now the Netherlands and other European countries are facing a new energy transition, from the gas to clean energy, like solar and wind. Also, if we want to save energy, maybe we can try to make the building smarter, more intelligent, so they can adjust energy consumption themselves; and the concept work at home. All these create some new chances for construction robotics, but mainly in maintenance, and operation. In construction processes, also. For example, some tasks, like beating, generates large noise. People don't like that, and they may protest, and the companies need to find some new technologies without noise.

L: Yes, I will consider that.

G: It just came to me that the companies' scale may also matter. I saw your slides before our meeting. One slide is about the technique of, what you call it ... construction factory? Yes, onsite construction factory. It will go up with the building rising. This technique originated from Japan. In the 1990s, Japan is leading in the construction robotics research and development. This technique was done by big companies. It is very heavy, maybe 5,000 tones, and very expensive. It is not a simple shell, but contains many other technologies, to move the building materials, to control the whole system. Only big companies have enough money for this kind of techniques. But also, it is also related the wages in Japan. The high wages made this technique still profitable, although it is expensive. So, the big companies will develop some large, complicated, expensive technologies. small companies cannot afford that.

You can put it in a 'cultural' part. It is a social culture.

L: Or in the economic group, it is related to the monopolization. Thanks for your time, Mr. van Gassel.

Reference

Maas, G. J., & van Gassel, F. J. (2011). Robotizing workforce in future built environments. *Proceedings of the 28th ISARC, Seoul, Korea*.

Set 2 Interviews to get knowledge for the current application of identified technologies

This set of interviews aims to get information about the current application of the technologies identified in Chapter 4. Two interviewees, one with an academic background and the other with a practice background, are interviewed.

Describing the identified technologies is time consuming, therefore, a set of slides are used to assist the interview. On each page, an identified technology is shown, with a picture, and some key words. Thus, the interviewees can soon understand what we are going to discuss. It turns out that this method works well.

Interview 5

Interviewee: Frans van Gassal

Time: 15:20-15:40, March 29th, 2017

Place: Vertigo 7th floor, TU Eindhoven

L: I have identified some technologies, that may be used to help to promote the robotic level in the assembly works. I want to know their application in the Dutch construction industry. the first is the wireless sensing, like RFID.

G: Yes. Wireless sensing, yes, it is used, but not very widely. It is mainly used in the supply chain. I know in some projects, they are used. Like, with a chip of tag attached to the materials, you can find it, or pick out from the storage. In some projects, they use bar code and square code to replace chips. Of course, the bar code cannot be detected by readers, just when it is transported into the site, you scan the code, and you know, it is onsite. But you cannot track it.

L: Why it is still not widely used? Is it expensive?

G: No, not expensive. I think just because people don't want change. It brings some benefits, but people prefer to do it in old ways.

BIM. yes, BIM, of course, is widely used now. But you should specify BIM.

L: I mean using BIM to assist the construction assembly work. Such as, BIM model contains the construction sequence, knowing that, the materials could be stored on site according to the sequence they will be used, then the work flow will be optimized, more fluent.

G: Well, if you say so, then BIM is used to help the assemble works. For instance, when you want something, some components or materials, you use the wireless reader, to find the thing you want, yes, this is wireless sensing we just talked, then, from BIM, you know the final position of it, where it should be assembled, and then, the workers know where to send it. This kind of uses exist, but there is not a, something like a text book, tell you what you should do. BIM have all the information of the projects, so any work that needs information could receive benefits by BIM.

The next, handling robots, yes, it has been tried in some projects. I presented it on ISARC symposium. You can find my presentation on my personal website. It is used, for handling the units of curtain wall.

L: But are they now widely used?

G: No. Just some trials. I think it is still not profitable, if you consider the cost of maintenance. Augmented reality, with glasses you can see something, but it is not there. It is also employed in some projects, but it is too expensive. Three or four years earlier, if I am right, the google glasses used to be popular, but very expensive, maybe more than one thousand euros. Today you don't hear google glasses anymore. It helps the onsite work, but, too expensive.

L: Not worthy at present.

G: No. Laser scanning, I think laser scanning is a bit like BIM. I mean, it is a tool. It is not like, let's say, handling robots, the handling robots is designed to help you to move, to lift the big things. But laser scanning, it is a tool. With the tool, you can get a digital model of the space. Then how you will use the model. Like in your slide, you say to compare the model with the BIM model and then inspect, yes, it is possible, although I have not heard someone use laser scanning like this, but it is possible; so like BIM, it support all the tasks which need information, laser scanning support the tasks which need the spatial models. The actors, contractors, need to find the new ways to use these technologies.

L: Yes, creative exploration.

G: Yes! Oh, the smart factory, yes, I know this. I also have something about this.

L: Has this kind of systems ever been applied in the Netherlands?

G: Yes, here. The Rotterdam Medical Center. It is automatic assembly system. It has been used. But in the Netherlands, it is not widely used. It is more proper for high rise. If you have thirty floors, then it is good; but if you have a house to build, it is not feasible. But in the Netherlands, high rise buildings are much less.

L: Then we can talk about the technologies for safety management.

G: I don't know much about the safety management field. But yes, as much as I know. I have to say, safety management is a very good field to study. It is focused in recent years. Because I am the secretary of the ISARC, I can see that this topic is more and more popular in the recent symposiums.

L: Thanks. Virtual reality is usually used in safety training. Do you have any idea that how it is applied in the Netherlands?

G: Yes, it is. At a very beginning stage. Some companies, like Volandis, and SGS, as I know, they are providing training for the contractors, because safety training is commendatory according to law. They have already begun to try to use virtual reality in training, also in test, to see whether the workers can react in a correct way. You know, it is very danger if you test the workers with hazards in real environment.

And augmented reality, I am not sure.

L: AR could be used to show the hazards, for instance, if there is a hole on the floor, then the glass will show a reminder of the edge to the worker to avoid falling, or something like this.

G: I have not heard any companies use it this way, but it is possible. But as I said, too expensive. Maybe in the future, I think it is plausible, but now, not feasible enough. But it is really a good application. So, people can know all the potential hazards information onsite. This help a lot.

L: And wireless sensing, again we talk about it. It could be used to track workers and objects onsite, to monitor the possible collisions between them.

G: Yes, that is used. I know in many companies, their equipment has similar technologies, so when some objects approach, other equipment or human being, an alarm will happen, to remind the operator. That's a lot. Sometimes I think they are integrated into the equipment.

BIM have the similar situation, as in assembly works. you use it as a resource of information, to help any work that need information. So, as BIM is now widely used, they are supporting safety management onsite. And in the future, they will be used more. What is virtual prototyping?

L: Well the term comes from manufacturing. The make a product in computer before actually product it, to see whether it will perform as designed. You can understand it as simulation.

G: Simulation, then I think yes. I know simulation is used a lot, especially for energy consumption, but also in other fields, so in safety management, there should be no problem. I don't know exactly.

L: The final one is gesture monitoring. By monitoring the onsite workers' motion, and compare their motion with the average motion in database, the uncommon pattern will be identified, and these uncommon data may reveal covert hazards, such as, if there is a working zone, very close to an edge, and the safety planning doesn't figure this out; generally, workers are required to report such kind of dangers, but if the danger is not obvious, sometimes workers will miss it, and thus, the remining hazards may cause accident when the condition is changed. Also, it could be used to correct the workers' gestures, so they can avoid some chronic hurts.

G: This is interesting, but I have not heard any practice of that in the Netherlands, maybe because I'm not in this field very much.

L: Okay, that's all the technologies I want to know. Thanks very much, I will ask somebody else about the safety management technologies in the Netherlands.

Interview 6

Interviewee: Michel Meijer

Time: 12:00-13:00, April 21th, 2017

Place: Dura Vermeer, Rotterdam Airport

(Introduction of the research, and available technologies)

Last time I talked with Professor van Gassel from TUE, he said that most of these technologies have been already tried in the Netherlands but not all of them are widely employed. so, this is an important part of our meeting today, to talk about the states of the arts of their application, and the factors that drive or impede their application. The first is wireless sensing technology, including the RFID, GPS, and something else. They could be used to pick out the correct building components, or trace the objects in the construction process. Do the wireless sensing technologies have been widely used in the Netherlands?

M: No, it is not widely used. We are one of the I believe five biggest construction companies from the Netherlands, you see some investigation in the use of RFIDs, in for example the material on the construction site, or in the helmet or clothes of the people working on the construction site, so we can track their movements, and see how to use the data come from the RFIDs, to make more efficient plan on the construction site. What's the difficulty in trying to use that is that the Dutch law also prohibits us from using that kind of data because of privacy concerns. It is the privacy law that makes it difficult. So, we've started doing some pioneer projects, by people with RFIDs in their clothes to see how they move on the construction site, and we put them in the materials we used to complete the building. if you ask whether it has been widely used in the Dutch market? No, it isn't. if you see the bigger construction sites, they are investing projects like this, because they see possibility to make their products and their process of building the construction more efficient. So, it is not that we need RFID, but we need the data, which is collected from the RFID. So, if you see the wireless sensing we are using right now, just in pilot phase we are using them to trace objects on site.

Another thing, I don't whether you can put it in wireless sensing. Our onsite operators now use some terminal devices, such as IPAD, to check the information from our BIM products, there is a lot of information that you can use. you can walk to the building, with the device you find all the information about the building. but that's not really wireless sensing, that more about information science.

L: Yes, it is. And actually, my next topic is BIM.

M: Ah, yes. We started working with the possibility if we make the measurements that's we make the model, then we go outside, we don't use laser, or other old-school equipment anymore, we just take IPAD, with GPS coordinator so that we know where to put the construction. it is probably more accurate than LiDar. We also have some buildings that are measured by GPS and our BIM model.

If you see the possibility of BIM, we have a contract with Autodesk, it is a contract that we are able to use all their beta version for all their programs, there are only two construction companies in the Netherlands have such kind of contracts, the other one is TBI, another big Dutch construction company. We also have possibility to give tips ad advises how to develop the products. So, we are doing calculations with the model, we have a virtual… how do you say, simulation, the entire simulation with the construction before we start it on the site. We can report issues, and the product, there are more than twenty options, the planning part, the document part, everything is related and connected to the model. The model is becoming the primary information carrier in our entire process. that is a big change, you can compare it to like three or four years ago, you were just drawing with AutoCAD, however right now, everything is information, every part is more linked to the information. And of course, in the assembly process, the BIM could also provide information support to the operators. But there are a lot of creative use of BIM, I mean, there is not a paper saying that you can do this or that with BIM, sometimes you need to explore the new application in different tasks, by like, brainstorm, and test your new idea in practice, and to confirm it helps or not. If it works, then you have a new method to do the work. Sometimes what we need is imagination, about how to employ BIM. Like the applications of BIM you mentioned on your slide, they are possible, and not necessarily expensive, but first, you have to be able to 'invent' it. I mean BIM is an open technology, and everyone knows how it works; whether we are smart enough to figure out some new methods, using BIM to assist achieving our purpose, that matters.

L: Does this application currently employed by many projects?

M: Yes, but mostly, by the big contractors. Because you have to a license you have to buy is expensive, software is also expensive, and you need right hardware as well, the smaller companies, they don't have enough money, and cannot afford the new technologies. that is a big difference between big and small companies.

L: Is BIM already legally obligatory in the Dutch construction? I know in some countries it has already been obligatory.

M: If you work for the government, you have use the software like this, so, it depends on who is your client. We just say that the bigger contractors are more likely to use big, but it is similar for the developers as well. The bigger developers have more potential to use BIM in their projects. But I believe that BIM will be widely used in the future. the trend of informatization in the construction industry is the fundamental driver of BIM's application. BIM is a zone with great potential, you can explore its creative use, to solve the problem that you face, sometimes combined with other technologies.

I saw the slide of laser scanning inspection. We use it as well. We have our own company that use laser to scan the entire old buildings or the buildings we finished, or for road as well, so you can put it in your car, and drive on like twenty kilometers an hour, through the entire area then you get a model with all dots, and then put it into specific companies, who is responsible to process the data then we have a complete model. One of the examples I have been told is that it could be used to scan all kinds of warehouses, for the Dutch government, where they put the salt inside, which used to melt the ice and snow on road. We use the scanners to inspect all the buildings, because we want to know whether the buildings were standing right, and whether any maintenance needed. and because we scanned all the warehouses through the country, we have a good model and overview of the possible maintenance that we need. Then they saw the models, as you have scanned the entire area of buildings, you can see how much its holds inside, in the buildings, so they also use the models to determine how much salt are there in the warehouse, so they could see whether they have enough salt. It is pretty accurate, it is like a photograph.

If you have some old buildings, you can put the laser scanners in front of them every month or every half year, you can see what happens to the building, because of the wind, the ground…usually we use the laser to monitor, and we can use it for maintenance report. We use it mainly for monitoring, for example, to monitor the old buildings to see whether they need a maintenance. In the assembly process, it could be used to track the process, to see where we are in the schedule.

L: Is it affordable for some small companies?

M: It was expensive, but right now, because of the new development, the laser technique becomes more accurate but also cheaper, I don't know the exact prices, but I believe that you can buy such a scanner at 30,000 or 40,000 euros. If you use it to measure 10 or 20 buildings, it will be way more expensive than you hire people to do that, and less accurate as well.

L: In literature, it is mentioned that using scanning model to compare with design model to inspect.

M: Yes, it is an application we are looking into right now. You can use laser like this, but also you can use a drone, with laser techniques, if you want to know how far your building is, and then you can also see the production from today, or last week, or last month, and you can compare them, with GPS coordinate.

The scanning technique is becoming, I think the possibility of using scanning techniques become wider and bigger than we than we are using them today.

L: Okay, then we come to the handling robots. how is the application of handling robots in the Netherlands?

M: We use this kind of products for some components, for example the doors, the entry door of buildings are usually much heavier than the ones inside of the building, and we need something to help to convey that. I think the robots with heavy lifting will become more interesting because the Dutch law says that you are not allowed to lift heavy objects, for each person, you are allowed to lift twenty or twenty-five kilos. So if you need to lift something like fifty kilos, you always need two persons, or a handing robot.

L: I guess for the contractors, handling robots will be cheaper than employ more labors in the Netherlands?

M: Yes, that maybe the most powerful motivation, but also, we are more motivated by the Dutch law we just mentioned, if the construction site inspection sector of the government find you don't obey a law, you get a fine. What's the difficulties in using this kind of robot, is that the construction is onsite, and the robots like this weigh a lot of kilos as well, so if you have to put this robot inside your building, then they are too big, and not really movable, not flexible enough to use onsite. For example, if you build this wall, and you cannot give the work totally to the robots, because when it is finished, the door is too narrow for the robots to get out. so that's a problem.

L: So right now, how to handle the heavy lift onsite? Just by more workers?

M: Yes, by many people, or by a simple, you can call it robot, with a frame, and wheels, which is employed to move the heavy objects.

L: so basically, the impeding factor is technical issue.

M: Yes, it's technical issue. If they can be smaller, and more flexible, it will be easier to use them, and you can make sure that they can get out of the building. if you put them on the first floor, I don't know how it could be moved out, it cannot walk down stairs. So, they have to be smaller and more flexible.

L: Any progress on this direction?

M: I saw something on YouTube, that they use half-man-half-machine, they put a baggage on human workers, with robotic arms, combined the robots and human workers. That will be much easier to be used inside the buildings.

L: So that's more like a human-robot-interaction, which is the next topic.

M: this is something that almost every companies is using. If you see the cranes, the operators don't need to be in the cranes anymore, you can use remote control, with phone, or IPAD, to make sure that the crane send the objects to the correct spot.

L: And do you know something about the single task robot, like welding robots, or bolting robots?

M: I have never saw such robots onsite. If you see the subcontractor we working with, who will build the windows, the concrete walls, everything, most of them are done by single task robots, but all in prefabrication factories.

L: Then augmented reality, is it employed in practice?

M: At this point, mostly in construction we use virtual reality, for selling houses. If you look at the BIM models, you can make the outcome commercial well, so you can give people glasses and they can walk into the building virtually, to see how the space is and how is everything. AR is a bit difficult, we are going to start a pilot within a few month, in which the workers will have AR devices, you can see where you will drill a hole, where you should put the door, where to put the electrical part, everything. So, we are talking about the pioneer, in practice it has not been used. Because it is quite expensive to equip the onsite workers with AR devices. At this point, we use a lot of IPAD, so they can look into the building information model. In the future, I think this will definitely be something that we are looking into. So that everyone has the same information in real time. now, AR devices is too expensive to be widely used at this point, and they are vulnerable, very easy to be broken. But I believe in the future it will be affordable. There are now a lot of technologies that can make it smaller, and cheaper.

L: What's interesting is that the papers about AR and VR had already appeared since the 1990s, but we just see they are going to be widely used today.

M: Well I think one of the main things of the culture within the different companies, and the people that have to work with it. if you have younger people within your company, they are more willing to use these type of program and technology, in construction there are people who are not into technology, and computer stuff, so for them, it is quite difficult to adapt to these technologies, because they have been used to working with papers drawings, for like thirty years. For them, this is how they do it, and how their work is. So, you have a lot of people that you have to convince, it is better for them, and better for the company, better for the product, better for the clients. I think that is one of the most difficult parts in changing the way how these people looking at these technologies. so that's why if we want to adopt a technology, we start from a pilot. When the pilot is successful, we are going to tell the colleague this is really great. It is difficult to use the top-down strategy, because people don't see the urgency before themselves to use these technologies.

L: As many people claimed, the construction industry is conservative.

M: Yes, unfortunately. In the job of mine in Dura Vermeer, I see that as well. Even things that have nothing to do with technology, which like if you tell people to walk to the left, instead of walking to the right, they are really traditional. You really need some ambassadors or some people who are really into these kinds of technologies, to make the deviate from the traditional path.

L: Finally, the construction factory. I heard it is used in the Rotterdam Medical Centre.

M: Yes, it is proper for the project. Because the building went up, with standard floor plans, that's more proper. Because the equipment is really expensive. If you have look at the Dutch city, we don't have that many big or high buildings. I don't know whether there are some other buildings, using this kind of technology. Another example I can imagine, but not for buildings, but for tunnels. We drilled the tunnel with Zublin, another German construction company, we drilled the tunnel from Den Haag to Rotterdam for the metro. To drill this tunnel, it was I think 120 meter, you can compare it as a factory, that there was a driller in front, and everything came behind, for putting concrete, putting prefab component at right spot, it is like a moving factory. So you can see a lot examples in tunnels but not so much in buildings in the Netherlands.

L: Okay, no more new technologies for assembly. We can go to safety management.

M: Okay. I just said, big companies can afford more investment in technology development. For safety, it is similar. The big companies are more able to invest in that. They are also more motivated to do that than small ones. Because you can imagine, the chance of onsite injuries is not very high, maybe higher than other industries, but not everyday. So let's say 10%. If you are a one-person company, then for 90% possibilities the money you spend in safety will do nothing. But if you have one hundred employees, then the possibility will be, how to say that, er, 90% raised to the one hundredth power, right? If you know the probability theory, you can calculate that, which is much lower than 90%. Also, they enjoy a scale economy, for instance, some devices, can be shared by ten workers, but you have one worker you need to buy one. then the efficiency is low. So, the big companies get more benefits from safety investment, and enjoy a lower average cost for each worker.

So the first tech is VR. As we talked, VR is already applied in the industry, including our company is using it. in safety training, I think there should be, but I'm not very clear. What I'm sure is that it is not widely used.

L: What do you think impedes its wide application?

M: I don't think there is any technical or financial difficulty. The cost is affordable, and what's also important, the VR is always used offsite, is not likely to be broken. So no problem. that's why I'm thinking there should be some suppliers provide such service, training workers in virtual reality. You know, most of the companies don't keep in-house training abilities.

AR, similar to what we have discussed, is possible, but too expensive to be used onsite. And if you are not careful enough, then, an expensive glass will be, Pa! But I think, AR will definitely be widely used in the future, it enables the workers to share all the onsite information.

L: Okay. And what about BIM and prototyping. I think these two are closely related.

M: Well BIM, as we said, is open to everybody, but requires creative use. so where you need information, then BIM gives you information. But you need to think about first, how to use the information.

L: Yes, I think I understand.

M: Virtual Prototyping, I see your explanation, it is like simulation?

L: My understanding, yes. To simulate the process before the construction actually begin.

M: Yes, it is used. We actually have several pilot projects using it to simulate the process to find possible dangers, actually the safety simulation is also integrated into the beta version software I mentioned. But it is just some pilot projects.

L: Any barriers for its application?

M: Well we always need pilots. We try something, if it is good, then we use it and share it. so, it just needs some time. The proximity detection is common. You can sometimes see onsite, a, let's say, excavator, when its distance with a worker, an alarm is made to remind the operator.

Gesture monitoring, according to your description, I have not heard of that. So, I guess it is not employed. but I'm not very sure.

L: Okay, I think that's all the technologies we need to talk. Thank you very much for your time!

Set 3 Interviews to construct narratives for scenarios

Factors identified by the first set of interviews are assessed by the six interviewees, to evaluate their impact and predictability. Then, with two selected factors, Artificial intelligence and Integration of the construction industry, a scenario matrix is established. This set of interviews aims to generate some inputs to make narratives for the scenarios. Therefore, the discussion will concentrate on three topics:

- How does Artificial intelligence affect construction robotics?
- How does Integration of the construction industry affect construction robotics?
- How do the two factors interact with each other?

Interview 7

Interviewee: Aant van der Zee

Time: 9:30-10:30, April 17th, 2017

Place: Vertigo 9.14, TU Eindhoven

(Introduction of the factors identification and assessment)

L: So, as I introduced, the two factors I used to plan the scenarios are artificial intelligence and integration of the construction industry. How do you think the development in Artificial Intelligence will affect the construction industry?

Z: Perhaps it will change, but I'm not sure if it will have a big impact on other things, also the construction industry, I am not sure whether it will have a very big impact, a life-changing impact on the construction industry. Nobody knows. We don't have really AI at the moment. They can play goal at the moment, that is the best we can do. I don't know what it can do in the construction industry; I will say to a computer I want to have a building, and I describe the building, and it will design a building? is that what we want? Or is AI capable of doing that?

L: Now people are talking about AI is taking over jobs from human labors…

Z: It was Monday I think, on the radio, they talk all day about robotics, also about AI, what influence it will be, that imagine also, that the computer would take a lot of places, jobs, but, what is happening, there are more jobs, only the low-tech, low jobs, really hard labor jobs, they are diminished; at the bottom, some layer will be taken over, but on the top, there will be new layer. We cannot imagine what kind of jobs they could be. So I think it will shift up, so all jobs need people with more education, so the simple jobs for the people don't have education, will be fewer.

L: As I know, there are already some 'intelligent' work has been taken by AI, for example, they could design the pipes and equipment automatically.

Z: Yes, there will be such replacement of jobs, somewhere down on the line of the process, there will be new job, making it possible that other jobs could be finished. It's like we go up the stairs from the low labor job to the higher labor jobs. We go constantly up. In the early 1900s, the automobile etc., cost labors, people worked then 50 hours a week, now we work 38 hours a week. And perhaps in fifteen years, we work twenty hours a week, and we will be happy. I don't know what will change and how we will adapt to it, but perhaps architecture is a way art than the present computers can handle.

I contact with TBI, they also have standardized house, they have what they call DNA of architect. They can say what kind of houses you like? To the buyers, they have Bauhaus, Mier, a lot of famous architects, okay, then I want to make a house standardized looks like a Bauhaus house. I think the layout of the houses are the same, just the façade. You can choose from what kind of architect you want it looks like. But it is a small step from the façade to a complete building. if you have an idea that we must have DNA of an architect, then we can make the building according to his beliefs. You know the movie Avatar, the actors were completely scanned, digitalized, they used that images for the movie, used a lot of digitalized actors to make the movie. Then is it possible that we can have a movie without actors. Just you scan an actor and you have a model in your computer and can you make a movie with only digital actors. That is out of construction industry but it is how far can we go, do we want it. we have AI and other algorithm, which can learn that something architects or actors can do. It can design your house. So you don't have a design cost anymore and you just have a AI drawing it.

L: well I looked up some literature about AI. They can be classified into two types, the weak ones and strong ones. The weak AI is something like google search, you give it words and it analyzes it and return the results using databases; strong ones refers to those with self-consciousness. So, with such a AI, maybe it is not surprising that it could do some creative works.

Z: Yes, that's why we don't know what it can do because we are at early stages, a AI can play goal is the best we have at the moment, play the most difficult gay and it can win.

L: This is why the participants in assessment of the factors think AI is an unpredictable factor, in twenty years we may face a high developed AI and low developed AI, it is difficult to say. That's the reason I choose the strategy to cover a wide spectrum, to explore the possibility as wide as possible.

The other factor is the integration of the construction industry. In this research, this factor refers to the trend in the construction industry that the suppliers tend to provide standard products, and they totally control the producing process. Thus, the construction industry works in a way more similar to the manufacturing industry. I the assessment of factors, the participating experts think this method will have big impact on construction robotics. How do you think the integration level will affect the industry?

Z: It is possible, there are a lot of students who are trying to make buildings like a library, and you can take and make your own houses. But I'm not sure if people like that. Now, the owners of houses like to pinpoint that is my house, so it must be different from the rest. Perhaps that could be done by change or alternate small components, say the color of the door, perhaps that is enough but perhaps you have to make bigger changes. Then what do we like? If you go to Belgium, they construct their city in quite a different way. We have a committee here to judge whether a building is well fits the environment, whether it has a nice façade, etc. do we like a city looks like a Belgium city? If we don't, it will be difficult to integrates all kinds of the buildings. You want to have a way to pinpoint your house, but also, you want to be the same with your neighbor.

L: Yes, last time you also talked about this issue, that the personality that people are pursuing. But I'm wondering, in the cellphone industry, or car industry, everybody is using almost the same product, but we are fine with that. Maybe cellphone is smaller but houses are something more important?

Z: Yes, that's how we see house. Cellphone is just an item you use, or a pencil, you don't mind if you have the same pen with someone else, you can also buy ten at one time, exactly the same pens; a car is a bit more like a home, you spend a lot of time in your car, somehow people like to show in what way they are living. I think if you go further then you get the house, you have the same thing: people like to show off, this is my idea, somehow you can't escape that it is also the same with your neighbors'. The balance point between the two conflicting ideas in people's mind, that will must happen in the future. it is 'I must pinpoint that is my house, it must be totally different from others' houses', that's my demand, or 'I don't care it is the same, with a different color on the door it is enough to show that is my house'.

L: Yes, it depends on the weights of the two ends. The massive production maybe cheaper, but it loses personality.

Z: Yes, so for each person there will be a balance point, he will say, that's enough. It is personality enough for me, and it is cheap enough to make it affordable. The future will tell where the balance is.

And, I don't think there will be a single global company who will control the whole market. it can't be done by a global company. I worked also in Germany and the difference with the Netherlands is very big.

L: Also the climate.

Z: Yes, maybe climate, but mainly how you look at the buildings, what you expect to have, that's quite different. So, I can't imagine there will be a global company who like Apple or Sumsung, making all the products for the whole world. I don't think it can happen on the global level. The nation-wide, I think it is possible, but it also has to face some legal limitation, it's a monopolization. So, I don't know whether it is advisable. You must be a company who has found the solution to make the prefabrication, make possible what everybody wants, for little money and place it in no time, anywhere on the globe, I don't think that will be realized, at least not in the near future. we don't know what will happen in the future. maybe because of the global warming, and we have to build a few big sky domes and all people will live within these domes, maybe then, it is possible to accommodate all the population in a universal product. So, on national level, I think it is possible, but there will be always some small companies left, for maintenance, or for some rich people who want to have very different house.

L: there is another fold in the meaning of integration, that is the integration of the construction process. now the process is fragmented, involved by many actors, from the design phase, building phase, operating and maintenance phases, introducing more uncertainties. So, if in the future, if we have fewer contractors and they expand their business to other fields, integrating the whole process, the whole chain into one company's control, maybe that will affect the construction industry, making it less diverse and more like car industry.

Z: Right now, the big contractors, they have a lot of satellite firms, doing the jobs for painting, insulation, heating, cooling, etc. because they cannot do it completely in the factories, then you have to ask the question, is it possible to have only a few firms make all the buildings in the Netherlands. Then how that will happen, how easy it can connect to sub firms to do the jobs, like I will purchase your firm as part of my company and you have to do what I like you to do and how I want to do it. perhaps it possible. In a way I think, perhaps I am old fashioned, it is just the construction industry who works in this way. We always look at the car industry, and say, they are so far and we are here. I think making a car is quite different than making a house. Because a building, a project is unique. When you make a project, all the circumstance, the constraints, will be complete different. So, I'm not sure looking at the car industry is a good way to discuss the automation in construction. They are quite different to be compared. It's not that easy to say, they are that far and we need to go that direction. Because the way the car industry developed and evolved, with the management types, the way of fabrication, make the car industry what it is now. the building industry is quite different. You can't have enclosed environment, so you have always to work on the place where you have to construct you building. it's always somewhere else. Or you can choose standardized prefabrication, then you have one factory and you can move all the elements and you can put it onsite, but the last part of work it is onsite, isn't in a work shop. So, for cars, you get all the supplies to do it, and you make it there, and finish the product and you deliver the products; and for building, to make it onsite because it is big, you can't make it somewhere else, transport the whole building, so that is one big difference. You can do standardized components by prefabrication, but the last thing is always finished onsite, they can't be the same. The whole process will always be different than the car industry. the prefabrication part can be the same with car industry, but then you need to transport them, on truck, on lorry, to location, and then you start again, in the open air, put them together. There are two different ways for construction, one in indoor environment and the other must in open environment, there will be huge impact on, let's say, painting jobs, or heating. There will be, on spot where the building will be made. So, you can't paint your components already, or some other works. So, there are a number of companies who can't do their work in their prefabrication.

L: There will always be some work left onsite.

Z: Yes. The main body of the job can be owned by the big firm; but the small companies, I don't think the big ones want to own them. it doesn't influence their processes, so that's something else. And I think those companies will always be on their own, and will not be purchased by the big companies. Because that is at the end of the process, being the finishing touch, it doesn't influence their job, they have to put it together, it is there, there are ten firms to the next job onsite, it doesn't influence their way of working because they have made it prefabricated, the building, and then other jobs.

L: You mean the finishing works can be done by some local companies after the main structure is done. And these works less influence the whole construction and therefore, the big firms don't care.

Z: I think that will happen, as we discussed, the buildings will be standardized, etc., but not completely, even within the car industry. if I buy a car, then I can do my own staff again. For example, I can paint the car, I can decorate it, etc. it is the same with building. you can paint it, or decorate it yourself, I can adjust the building I bought myself. I mean the product integration could be limited in the main structure of the building, and leave some onsite works to the clients, to cater their own taste. As for houses, everybody has his own idea about the kitchen and bathroom, if you buy a house from a previous owner, very likely you will adjust the kitchen and bathroom to adjust to yourself requirements.

L: So far, in my opinion, I think the two dimensions of the scenario planning, are actually, two ways to promote the robotics level in construction. The integration dimension, tries to move the works into more standard, more structured environments, and a more fixed process, so to reduce the uncertainty in the dynamic building environments; the second dimension, however, is to improve the robots' capability, enabling them to be more adaptable to the unstructured onsite environments. How do you think these two could be interact with each other?

Z: I think they need each other. High integration will ask for a high AI, and a high AI will ask for a high integration. They need each other because the high integration, people cannot understand it anymore, what is happening and how is it happening, only AI can understand and manage it. maybe I read too much science fiction, but that's my idea. If you have AI in building industry, I think then it is a step to high integration. It also works the other around. If you have high integration, then you need high AI level because we cannot handle it anymore. It goes too fast, that we cannot respond directly.

L: Okay, thanks for your help!

Interview 8

Interviewee: Michiel Bottema

Time: 13:00-14:00, April 17th, 2017

Place: Heijmans office, s-Hertogenbosch

(Introduction of the factors identification and assessment)

L: So, as I introduced, the two factors I used to plan the scenarios are artificial intelligence and integration of the construction industry. In this research, this factor refers to the trend in the construction industry that the suppliers tend to provide standard products, and they totally control the producing process. Thus, the construction industry works in a way more similar to the manufacturing industry. I the assessment of factors, the participating experts think this method will have big impact on construction robotics. How do you think the integration level will affect the industry?

B: Then what do you more focused? From my point of view, the gaining on integration is more about is not from the standardized product but more standardized process, which different participants in design and construction phases, work together as one. in the current situation, you see a lot of hand over of information, from one party to the next party, according to BIM, we see the development that you get integrated processes, where you don't own your own information anymore, the information is being owned by the project, used according to multiple disciplines, by multiple companies, working on the same project. That is I think more the integration we are heading towards.

L: I take these two aspects both.

B: The standard prefabrication and components is also a trend going on, but I see more benefits from the integration of processes than integrated products. And also, that depends on what sector you are in. I mean, if I'm involved with the non-residential construction, every hospital, every university building, and every governmental building, is unique, and is less likely to be standardized than residential.

L: What else features do you think integration of construction will bring?

B: What I see is that there are two games, two big developments. One is offering more quality to the end users, that means the construction industry needs to more focus on the clients and the clients' demands than currently, that is one movement which is going to be help by the use of AI and integration. The other one is the profitability of the industry.

L: Profitability.

B: Needs to go up. Our margin profit is so little compared to the risks we have in the projects, that's why we really need a much better control of our processes, and the quality of the product we are making, these going to help. Traditionally people focus on failure cost, in the construction industry failure cost means I did something wrong and I need to repair it, currently about 12% of the construction budget. It is in every aspect preventable, if you get better information, or use information in a better way, you can reduce that, reduce its percentage. But that is not the big win. The big win is the fact that currently we have a lot of waste in design and production processes.

L: Yes, last time somebody talked with me, that the profit of the construction industry is 3% or 4%, but the failure cost, the waste is about 12%, so if you improve the waste slightly, you cause a big improvement in profit.

B: Yes, but most people are not talking about the inefficiency in the projects. And I think that add up to at least 30%. That's the inefficiency we have used to. When the construction worker, working on the building sites, for him it is very normal to go back to the office, like five times a day, to get information, or new screw, or new types of equipment, or something else. That all built into our normal pricing of the work is doing. While if we know what a certain construction worker need to do in one day, you can provide him just the information he needs to finish that task, provide him right material, right equipment. so that he can have a full day of work. the way we do our work now, in the whole industry, in design, in construction, in manufacturing, there are so much waste in the processes, we just find it normal, people don't look at it because it is normal. No one is questioning whether it is reasonable. That's where I want to improve. The failure cost is just an extra bonus. If you add up failure costs, and that's the waste in the processes, you've got 40%. I don't have hard foundation for what I'm saying, I want to say at last, every euro we spend on the construction, building, 40% is not necessary. Just because the process is not integrated, we don't use information in a correct way and we don't mind. If you compare that 40% we can gain to the 1% or 2% profit margin, it's strange.

L: Well maybe we care that, but there is not technology sufficient for us to manage that, I guess.

B: I think there are techniques available to process it, I think technology is not holding us back. As you see, around the world, the construction industry is very traditional industry, accompanied by the less traditional technologies coming out way, you see it's being populated, with people who like to solve problems. That's why the choose to join the construction industry, they like soft bottles. And what you now currently see, is that they don't want to make it less complicated, because they like the complexity of it. They are self-feeling proficiency, so to say, the construction industry, traces some serving kind of people, because of its complexity, everything, every time, over and over again, extremely like the first time, that attracts a kind of people, who like that. They will preserve that, because that's what they like, the only way to overcome that, is to get more IT persons, interested in construction industry, and sharing them that, if you get information, you build whole other processes than we are having currently. for instance, in our company, we do the HAVC system we design, we manufacturing the cells and we assemble them ourselves. It's all designed by 3D models, nowadays, we are starting to do analysis, simulations, based on the computer model we have got, we've got a company in our team so we are able to engineer all the equipment needed to hang that's piping, to the walls and to the ceilings, and to deliver all the materials we need in one box, each room as one box with all the materials we need for that room, and even it is possible to use the computer model to decide where they need to drill a whole, we've got automated survey systems, which can automatically point a laser on the ceiling where to drill a hole, the only thing we need to do is to invent a drone, conducting the actual drilling.

L: Is this system widely applied in your projects or just at the developing phase?

B: No, it's a combination of already available improving technologies, it just adds up all the different technologies, to be applied on new projects. Automated surveying is already being done, but not for the HAVC system, the last piece of technology we still need to invent, is a drone who can actually drill a hole. Then you can tell the totally automated process, designing your HVAC systems, up to drilling a hole, you only need one operator or worker to conduct that. I'm being laughed at, in the company, for thinking that's possible and that's going to happen. And they pushed it from the table within one minute, ah, that's not going to happen. But I know for sure it is going to happen.

L: I guess that is what they called 'conservativeness' in construction.

B: Yes. All technology is already available, the only difficult part is mounting drill a hole of a drone, and being able to put enough pressure, to drill actually into concrete. Honestly, I think some people in the construction industry, don't want these problems to be solved. They like complexity. That's why the selected the construction industry.

L: this is something new to me. I knew that people don't like to change, but I didn't know that they like complexity.

B: They like complexity. It's not something we do intentionally, they choose the construction industry because of the complexity and the fact that they build something new every time, never two times the same, now they say, ah, we are going to do that two times the same! That's what the choose this industry for. And it is really not a conscious decision. Something they do and act certainly. The fact is that in the construction industry, the people make the most money, are those who are best in solving these complex problems, the complex problem, the more he earns for doing that. So, he has no motivation to make it less complex. Why should he? I sometimes think that they make it complex on purpose. So, they can solve it afterwards. Make a puzzle, so you can solve it.

B: One of the questions is that we divide our work into many different companies. When we do a certain design in construction, it is perhaps a chain of thirty, forty, fifty different companies doing one small piece of work. mostly, the internal processes, are not well documented, companies don't actually know what information they need to do their work, so they just ask all the information available, and find out what they actually need. So, what you see is that there are a lot of handing over of information. Companies don't precisely know which information is valuable to them. you also see a lot of information is being spoiled, or not accurate, because they don't know what information they need and which information is accurate, they also tend to collect new information, build information database on their own, and the next companies on the chain doing the same, and the next doing the same, and that really holding back the innovation in our industry. so from my point of view, what we are doing, is building one, we are working for one information model, with objective that once information that is produced, you store it, you preserve it, so it can be used by other companies working on the same project. That means you have to store your information in a way that accessible for other companies, it is easy to be maintained, and you need to have the same language, I mean everyone understand what certain type of information mean, so that's what I'm working on, it will get better as soon as we are able to do that. People don't need to collect new information, built their own information structures, and can built more efficient processes. Perhaps I'm now even again on the innovation part, but it comes to actually using the information, I think we only make the first small steps.

L: Then I think that is about integration dimension. What about the AI dimension. How do you think the artificial intelligence will affect the construction industry? Maybe the development of AI helps to control the robots and drones in recent future?

B: Then the construction process will be greatly automated, less workers needed, that's for sure. And also, from the perspective of the integration, it also helps. I can give a, not a strong example, when it is windy, you know, in the Netherlands, it is a lot of wind. It has an impact on the number of hours that we can use our cranes on construction sites. What I can imagine is that it will be very easy to create based on a weather notices, you can predict the amount of production you can achieve on the construction site. You could adjust your schedule, to take into account the weather forecast. We can head towards twenty-four-hour economy, our construction sites are twenty four hours a day open, it gets an opportunity to get a dynamic construction schedule, take weather forecast into consideration. That's not a strong concept, but something similar may happen. Seventeen years ago, when I first start the working, our supervisors on the construction sites, they got a weather fax, from the fax machine every morning, at that moment, we are going to see, what production could be expected for that day. Nowadays, we can have weather forecast ten or twenty days ahead, and calculate different scenarios, and how we can deal with that. Before it cuts a force period, we have got in situ concrete, not prefabricated, but pour on the construction site, the concrete doesn't get hard, when it below o degree. So when it below o degree, construction sites usually cannot continue, because you can't use concrete. So what you see is that the construction projects, work hard during the fall so that they can do as much as possible before winter comes. Now when you can better predict, which period you can and cannot work, you are able to be better making different scenarios, or even automatically decides you are not going to use in situ concrete, but prefabricated concrete instead, because you want to do the construction project in the winter time. and you also need artificial intelligence, to automatically redesign the for in situ concrete to prefabricated concrete. That's I imagine how it will work, to conduct the automated construction processes.

But still, it will be very difficult to imagine what will happen. Now we are totally reply on iphone, but ten years ago, nobody saw that, so ten years from now, what equipment, material, technology, may be greatly different with they are now.

L: Good. Then this case could also be used to explain the interaction between these two factors. Thanks for your time.

Appendix D Questionnaire for factors assessment

Title: The factors which impact the development of construction robotics technologies

Dear Sir / Madam,

thank you for taking part in the research. By filling out this 10-15 minutes' survey, you will help me obtain some crucial information. As I have introduced, to cover the possible landscapes of construction robotics technologies in 2030, two factors need to be identified to establish a set of scenarios, which will be used as a base for the further research.

According to the previous interviews, 8 factors that may affect the direction of construction robotics technologies' development has been summarized. This survey aims to assess these factors from two perspectives: impact and predictability. For each factor, there are three questions, focusing on its **impact** (on the future development of construction robotics technology), **predictability** and **possible future development** (if possible) respectively. Each question could be answered using a 7-point Likert scale. A brief description is given under the first question of each factor.
Factor 2, Regional growth, is able to be exactly predicted, therefore the latter two questions are left out. There are 23 questions in total.

Factor 1: Labor rights

The original purpose of construction robotics is to replace human labors in the construction industry. However, in the history, applications of technical innovations have always been accompanied by the topic 'machines are taking jobs from human workers'. The social pressure generated by such protests may affect the demand of construction robotics. To compromise the pressure, contractors may prefer to adopt the technologies that do not reduce working positions. For instance, BIM helps to improve performance in construction by managing building information, without reducing any positions; meanwhile, some human-replacing technologies, e.g. single task robots, are less likely to be adopted with the background. The shifts of the contractors' demand may apply an impact on the orientation of robotic technologies' in the future, from human-replacing to performance-improving.

Question 1: To what extent do you think the labor rights movements impacts the future development of construction robotics technologies? From 1 (No impact) to 7 (Extremely great impact).

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

Question 2: How predictable do you think the development of labor force movements is in the next decade in the Netherlands? From 1(Not predictable at all) to 7 (Highly predictable).

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

Question 3: How active do you think the development of labor right movements in the Netherlands will be in the next decade? From 1 (Not active at all) to 7 (Highly active), or 0 (difficult to say).

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 0 (Difficult to say)

Factor 2: Regional growth

Various demographic evolvements affect the demands on the local construction market differently. Growing population creates opportunities to construct new buildings; while in depressing regions, very rarely new buildings are constructed, with most of the construction activities concentrating in the fields of renovation, refurbishment, and maintenance. Robotic technologies required by the two types of construction practice are likely to evolve differently.

Question 4: To what extent do you think the regional growth impacts the future development of construction robotics technologies? From 1 (No impact) to 7 (Extremely great impact).

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

Artificial intelligence

Artificial intelligence is a key technical factor that may affect the future of construction robotics. It is always mentioned that the unstructured onsite environments impede the application of automation and robotics technologies in construction (V. R. P. Kumar, Balasubramanian, & Raj, 2016). Robots work depending on the program embedded in them. However, in an unpredictable circumstance, the preprogram cannot work well. Therefore, human labors are still required to assist the process. With the development of techniques in machine learning and thinking, these problems may be solved. With the assistance of by artificial intelligence, robots and robotic systems could learn automatically, being able to handle more complicated tasks. Thus, AI may completely change the construction robotics technologies.

At the same time, this factor is also controversial. The application of AI in construction practice brings ethic discussions. As Professor van der Zee mentioned in the interview: 'Do we allow the AI to make mistakes? We all learn from mistakes, as well as AI; who will be responsible for its mistakes?'.

Question 5: To what extent do you think the artificial intelligence impacts the future development of construction robotics technologies' development? From 1(No impact) to 7 (Extremely great impact)

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

Question 6: Factor 3: Artificial intelligence. How predictable do you think the development of artificial intelligence is? From 1(Not predictable at all) to 7 (Highly predictable).

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

Question 7: Factor 3: Artificial Intelligence. How do you think the Artificial Intelligence will develop in the next decade? From 1(No obvious development) to 7 (Great development), or 0 (Difficult to say)

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 0 (Difficult to say)

Additive manufacturing

Another more famous name of additive manufacturing is 3d printing. Although some pioneer projects have been implemented, large scale application in practice has not been realized. The most significant contribution of additive manufacturing is that the construction processes are no longer subjected to the specific crafts or equipment, but to only digital inputs; thus, the producing costs of customized product will be more or less the same with standardized ones, and individualized buildings will be promoted.

Question 8: Factor 4: Additive manufacturing. To what extent do you think the Additive manufacturing impacts the future development of construction robotics technologies' development? From 1(No impact) to 7 (Extremely great impact).

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

Question 9: How predictable do you think the development of additive manufacturing is in the next decade? From 1(Not predictable at all) to 7 (Highly predictable).

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

Question 10: How do you think the Additive manufacturing will develop in the next decade? From 1(No obvious development) to 7 (Could be widely used in construction practice), or 0 (Difficult to say)

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 0 (Difficult to say)

Energy supply and carbon emission

Energy consumption is concerned for three reasons. First, to guarantee the sustainable development of human civilization; second, to suppress the global warming; finally, to reduce the impact of possible high energy cost in the future. Therefore, new technologies are trying to find a balance point between energy-consumption and performance-improving. New technologies enhancing working efficiency or performance slightly with too much extra energy consumption are considered unworthy. However, in the future, if alternative energies, e.g. solar and nuclear power, are applied on large scale, this balance point may move to the performance-improving end.

Question 11: To what extent do you think this factor impacts the future development of construction robotics technologies' development? From 1(No impact) to 7 (Extremely great impact).

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

Question 12: How predictable do you think the development of this factor in the next decade? From 1(Not predictable at all) to 7 (Highly predictable).

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

Question 13: How do you think the alternative energy will evolve in the next decade? From 1(No obvious change) to 7 (Alternative energy could replace the fossil fuel on large scale), or 0 (Difficult to say)

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 0 (Difficult to say)

*Availability of employees in the construction industry**

In a circumstance where employees are in shortage, innovations tend to go further to the automatic direction to save labor cost. Here the term 'employees' refers not only the manual workers, so called 'blue collars', but also the 'white collars', if the technologies in the future are able to handle more intelligent works. The development of this factor is decided by multiple elements, for instance, the demographic evolvement, the immigration, economy pattern, as well as the attraction of the construction industry.

Question 14: To what extent do you think the availability of employees impacts the future development of construction robotics technologies' development? From 1(No impact) to 7 (Extremely great impact).

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

Question 15: How predictable do you think the development of this factor in the next decade? From 1(Not predictable at all) to 7 (Highly predictable).

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

Question 16: How do you think the availability of employees in the construction industry will evolve in the next decade? From 1(Very easily available) to 7 (extremely unavailable), or 0 (Difficult to say).

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 0 (Difficult to say)

Integration and globalization of the construction industry

Compared with the manufacturing industry, the construction industry is highly fragmented. The manufacturing industries, for instance, car manufacturing, organize themselves and the whole supply chain very effectively, because they work on standardized products; whereas in the construction industry, each project based on a unique assignment; after the project is finished, the contractor will move to the next one, with a different team from the previous one. Different assignments lead to unique products, while various teams lead to unique processes. With both product and team differ every time, the construction activities are highly fragmented. The experience accumulated in a project can hardly be employed in the next one. In recent years, some efforts of integration in the construction industry have been observed. For instance, some companies are beginning to provide full-prefabricated standard houses, including some international companies (e.g. IKEA and MUJI), as well as local ones, trying to integrate the products and producing processes, reduce the fragmentation of each project.

If this new business model becomes popular in the construction industry, it may drive the construction industry into a similar path with manufacturing industry, with many works moved from onsite environments to indoor circumstances. The robotics technologies will be greatly different.

Question 17: To what extent do you think this factor impacts the future development of construction robotics technologies' development? From 1(No impact) to 7 (Extremely great impact).

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

Question 18: How predictable do you think the integration and globalization of the construction industry of the construction industry is? From 0 (Not predictable at all) to 7 (Highly predictable).

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

Question 19: How do you think the construction industry will evolve in the next decade? From 1(highly fragmented) to 7 (highly integrated), or 0 (Difficult to say)

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 0 (Difficult to say)

Monopolization

Some interviewees mentioned the fact that big companies and small companies have different patterns in construction robotics research and development. The big companies are able to afford a higher research cost and initial investment than the small ones. Therefore, big companies are more likely to develop or adopt some expensive 'heavy technologies'. For instance, in the 1980s and 1990s, some leading top-scale construction companies in Japan developed the Construction Factory System to enhance the automatic and robotic level of onsite construction. The system is costly and heavy, very rarely adopted by smaller contractors, who are more interested in the 'light and smart technologies'. Thus, the extent of monopolization of the construction market may affect the robotic technologies' evolvement in the future.

Question 20: To what extent do you think the monopolization impacts the future development of construction robotics technologies' development? From 1(No impact) to 7 (Extremely great impact).

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

Question 21: How predictable do you think the monopolization is in the Netherlands in the next decade? From 0 (not predictable at all) to 7 (Highly predictable).

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

Question 22: How do you think the contractors' scale will evolve in the next decade in the Netherlands? From 0 (More small companies) to 7 (More big companies), or 0 (Difficult to say).

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 0 (Difficult to say)

Question 23: Are there any other factors in your mind affecting the future development of construction robotics technologies?

Appendix E Summary of the currently available technologies

Table E.1. Currently available technologies in construction assembly

	Identify	Convey and align	Connect	Inspect
Internet of Things (IoT)	**Working principle**: Be used to manage the inventory, picking out the target components or materials in shorter time; **Added value**: Shorten the time needed for identifying and locate the components;	**Working principle**: Be used to locate the current position of the components, thus the location information could be used to generate a convey path; Increase the efficiency of conveying process; improve safety; **Added value**: To track the material or components in the process of conveying, monitoring whether it is moved along the planned path;		
	Current application: Have been employed in separate projects, but not widely used, mainly because of the high initial cost and privacy-related regulation			
BIM	**Working principle**: Be employed to manage the inventory onsite, combined with sensing technologies; **Added value**: increase the awareness of the onsite inventory, decrease the management cost, make the construction process more fluent; **Current application**: not widely used due to the limitation from wireless sensing.	**Working principle**: Support the conveying process by providing related information, e.g. the final position of the components to generate path by together with the current position information; **Added value**: help to optimize the conveying process, thus improving the conveying efficiency; **Current application**: Has been employed.		**Working principle**: Be used as benchmark to inspect the assembly work, usually combined with imaging technologies, e.g. laser scanning; **Added value**: make the inspection process more intuitive and less time-consuming; increase the efficiency of inspection; **Current application**: Technically possible, but still rare.
Handling Robots/systems (A&R)		**Working principle**: Replace human labors in conveying phases; **Added value**: less time and labor force required; **Current application**: there have been some trials, but in practice rarely used, mainly because of the robots are cumbersome, and the handling system has not been fully developed.		
Human-Robot Interaction (HRI)		**Working principle**: assist the cooperation between human and robot; **Added value**: Combine the advantages of both human labor and robots; **Current application**: Has been used in some projects.		
Laser Scanning (L&P)				**Working principle**: digitally rebuild 3D as-built environment which could be compared with the BIM model to check whether the assembly work is done as designed. Photogrammetry can be used as an alternative of laser scanning to model the built environment. **Added value**: make the inspection process more intuitive and less time-consuming; increase the efficiency of inspection; **Current application:** Technically possible, but still rare.
Single Task Robots (A&R)			**Working principle**: replace human labor in some repetitive work; **Added value**: less labor force needed; **Current application**: the onsite application is rare.	
Augmented Reality (VR/AR)			**Working principle**: superimpose the digital 3D information to the physical environment by using wearable devices, then the building information is displayed intuitively as reference for workers so that they do not need to check assembly information in related documents; **Added value**: Make the assembling process more fluent, reduce the time needed. **Current application**: Have been tried, but still not very widely used.	
Construction Factory (A&R)	**Working principle**: Provide an indoor environment for the structure assembly works, which is more structured and less dynamic, less affected by weather; **Added value**: promote the adoption of some technologies which require manageable environmental conditions, increase the automation level of construction work, including the assembly work. **Current application**: Has been employed for several times, but not widely used in building practice. Used to be employed in tunneling.			
Bottom-up construction system (A&R)	**Working principle**: assemble the structure on the ground floor and then lift the assembled structure, then continue the assembly work on the ground floor. **Added value**: create a more stable and manageable construction environment (on the ground floor); **Current application**: emerging, not in practice.			

Table E.2. Currently available technologies in construction safety management

	Safety training	Safety planning	Hazards alarming	Proximity detection	Gesture monitoring
Virtual Reality (VR/AR)	Working principle: Provides a virtual environment for the trained workers to get familiar with the onsite safety issue and emergence from the first-person view; Added value: Improve the efficiency of safety training, reduce disturbances to construction work; Current application: Has been applied in practice	Working principle: Combined with BIM, to provide an opportunity for the safety managers and engineers to identify the risks from first -person view; Added value: Improve the efficiency and completeness of hazard identification; Current application: not widely used in the Netherlands.			
Augmented Reality (VR/AR)			Working principle: AR display the identified hazardous information from BIM superimposed on the real physical environment image to remind the onsite workers; Added value: Make the onsite hazards more intuitive and noticeable thus to reduce the potential accident. Current application: Several attempts have been seen, but still not widely used yet.		
BIM	Working principle: Provides 3d and 4d information for the establishment of virtual environment; Added value: enhance the efficiency of safety training Current application: Has been applied in practice	Working principle: To simulate the construction process to identify the the potential safety issue, using the 3d and 4d information provided by BIM. Added value: enhance the accuracy and efficiency of safety planning thus to manage the safety risks better; Current application: It is new for the Dutch construction industry, and has not been widely employed.			
Virtual Prototyping (S&A)					
Internet of Things (IoT)			Working principle: Send hazards information to the onsite movable devices to remind the onsite operators the potential danger. Added value: prevent the onsite accidents on the last second. Current application: is widely used in the Netherlands.	Working principle: track the hazardous objects to monitor their locations and postures in real time; Drawbacks: different technologies have different advantages, sometimes a combination of them are used, causing complication of devices. Expensive. Current application Added value: Increase the real-time awareness of the safety risks; Current application: Technically and financially possible, but limited by privacy-related rules.	
Wearable/Moving Devices (IoT)					Working principle: Monitor the motions of onsite workers to analyze the pattern of their postures, and compare to the general pattern from big data, to identify the potential hazards and the risks of MSDs. Added value: Enhance the accuracy of hazards identification; decrease the MSDs affection; Current application: Is still new to the Dutch construction industry, has not been used yet.
Big Data (BD)					

Appendix F Possible future evolvement of the currently available technologies

Table F.1. The probable evolvements of wireless sensing technologies in different scenarios

Wireless sensing			
Working principle	Is employed to identify the components or materials to manage the onsite inventory, and track their location in the conveying process.		
Current application	Have been applied, but not widespread.		
	Drivers	-	Demand for tracking and locating.
	Barriers	-	Conservativeness.
		-	Privacy code.
Future landscapes			
Scenario 1	Drivers	-	Existing driver remains;
		-	More complicated onsite inventory management.
	barriers	-	No new barriers identified.
	Evolvement	Rise. Reader-free systems are desired.	
Scenario 2	Drivers	-	Existing drivers remain;
		-	Controlling AIs of construction activities require a technique to identify objects.
	Barriers	-	No new barriers identified.
	Evolvement	Rise. Reader-free systems are desired.	
Scenario3	Drivers	-	Union of Scenario 1 and 2.
	Barriers	-	No new barriers identified.
	Evolvement	Rise. Reader-free systems are desired.	

Table F.2. The probable evolvements of BIM in different scenarios

BIM			
Working principle	Provide 3D and 4D information to assist related construction activities.		
Current application	Have been widely used in the Dutch construction industry, but not so much in assembly works.		
	Drivers	-	Demand for efficient information management.
	Barriers	-	Conservativeness.
Future landscapes			
Scenario 1, 2 and 3	Drivers	-	Existing drivers remain;
		-	AI's deep involvement in the construction process requires a database that can be understood by AI.
	barriers	-	No new barriers identified.
	Evolvement	Rise. BIM's application in construction assembly needs to be further explored, creatively.	

Table F.3. The probable evolvements of handling robots/robotic systems in different scenarios

Handling robots/robotic systems			
Working principle	Replace human labors in the labor-consuming handling works.		
Current application	Have emerged in a few projects in the Netherlands, but still very rarely employed.		
	Drivers	-	Demand for replacing human labors;
		-	Legal requirement (e.g. individual workers are not allowed to handle weight over 20kg)
	Barriers	-	Too cumbersome for the indoor environment;
		-	Not financially feasible.
Future landscapes			
Scenario 1	Drivers	-	Existing drivers remain;
		-	Tight labor supply;
		-	Remarkable progress in miniaturization.
	barriers	-	No new barriers identified.
	Evolvement	Rise. Evolve to be more interactive with human workers.	
Scenario 2 and 3	Drivers	-	Legal requirements;
		-	AI enables the robots to be more intelligent and adaptive to be used onsite;
		-	AI supports the development of swarm robots.
	Barriers	-	No new barriers identified.
	Evolvement	Rise. Evolve to be more intelligent, working without human intervention. Swarm robots will be a possible direction in the future.	

Table F.4. The probable evolvements of HRI in different scenarios

Human Robot Interaction technologies			
Working principle	Use sensors to support the cooperation between human workers and robots.		
Current application	Not widely applied in the Netherlands.		
	Drivers	-	Demand for the technology to enable human workers and robots to cooperate better.
	Barriers	-	Construction robots are rarely employed in the Netherlands.
Future landscapes			
Scenario 1	Drivers	-	Existing drivers remain;
		-	More human-robot-interaction on the construction site.
	barriers	-	No new barriers identified.
	Evolvement	Rise.	
Scenario 2 and 3	Drivers	-	No new drivers identified.
	Barriers	-	Reduced human workers.
	Evolvement	Decrease or even disappear.	

Table F.5. The probable evolvements of Laser scanning and photogrammetry in different scenarios

Laser scanning and photogrammetry			
Working principle	Scan the built environment to establish the as-is model digitally, and compare the model with designed BIM model, to check whether the work is done based on design.		
Current application	Has already been used.		
	Drivers	-	Demand for quick inspections.
	Barriers	-	Used to be expensive, but the price is affordable now.
Future landscapes			
Scenario 1	Drivers	-	Existing driver remains;
		-	Price is affordable.
	barriers	-	No new barriers identified.
	Evolvement	Rise. Photogrammetry, which has been replaced by laser scanners, will be reused to monitor assembly processes, combined with drones.	

Table F.6. The probable evolvements of single task robots in different scenarios

Single task robots			
Working principle	Use robots to replace human labors.		
Current application	Very rare in the Netherlands.		
	Drivers	-	Demand for replacing human labors.
	Barriers	-	Not intelligent enough to work onsite automatically.
Future landscapes			
Scenario 1	Drivers	-	Existing driver remains;
		-	Tight labor supply;
		-	The increase of HRI technologies.
	barriers	-	Existing barrier remain.
	Evolvement	Slightly rise. The single task robots are more interactive with human workers.	
Scenario 2 and 3	Drivers	-	Existing driver remain;
		-	AI enables the robots to work automatically, dealing with complicated onsite environments.
	Barriers	-	No new barriers identified.
	Evolvement	Rise. Swarm robots will be the new direction.	

Table F.7. The probable evolvements of Augmented Reality in different scenarios

Augmented Reality			
Working principle	Show digitally the designed information intuitively to onsite workers, so that they do not need to check 2D drawings to get information.		
Current application	A few trails have happened, at the elementary phase.		
	Drivers	-	Demand for visualizing the digital information.
	Barriers	-	Initial cost.
Future landscapes			
Scenario 1	Drivers	-	Existing driver remain;
		-	The price of AR device is becoming affordable.
	barriers	-	No new barriers identified.
	Evolvement	Rise. Expand from the conveying/connecting phases to the identifying and inspecting phases in construction assembly works.	
Scenario 2 and 3	Drivers	-	The same with Scenario 1.
	Barriers	-	Human workers' involvement in construction decrease, and therefore no demands for displaying information to workers.
	Evolvement	Decrease, but with small scale application in inspections.	

Table F.8. The probable evolvements of Construction Factory in different scenarios

Construction Factory			
Working principle	Provide indoor working environments for robotic and automatic technologies to be applied.		
Current application	Several attempts.		
	Drivers	-	Demand for applying automatic technologies in onsite working environments.
	Barriers	-	Heavy and expensive, not affordable for small companies.
		-	Demands for high rise buildings in the Netherlands is limited.
Future landscapes			
Scenario 1 and 3	Drivers	-	Existing driver remains;
		-	A Higher level of monopolization generates several big companies, which are able to afford the equipment;
		-	The technique is becoming lighter and less expensive, proper for smaller and low-rise buildings;
		-	More standardized buildings.
	barriers	-	Existing barriers remain.
	Evolvement	Rise slightly. In Scenario 3 the CF will be smarter, connected to the controlling AI, which enables operators to monitor the whole system in real time.	
Scenario 2	Drivers	-	No new drivers identified.
	Barriers	-	No new barriers identified.
	Evolvement	Remain.	

Table F.9. The probable evolvements of Bottom-up system in different scenarios

Bottom-up system		
Working principle	Construction works are done on the ground level and then the whole structure is lifted to continue the assembly work.	
Current application	Still not in practice	
	Drivers	- Proper for construction in intensive urban zone; - Enhance safety and quality of the construction; - No building material lifting.
	Barriers	- Not fully developed technique.
Future landscapes		
Scenario 1, 2 and 3	Drivers	- Existing driver remain; - Is likely to be developed further to be technically and economically feasible; - In all the three scenarios, construction in historic urban zones is an important part of construction activities.
	barriers	- No new barriers identified.
	Evolvement	Rise.

Table F.10 The evolvements of VR in different scenarios

Virtual reality		
Working principle	Enables the workers to experience the working environment intuitively offsite, to get the most out of the training.	
Current application	Is on the edge of booming.	
	Drivers	Demand for a method to observe from the first-person-view to experience the onsite environment more intuitively
	Barriers	- No barriers identified, and its application is booming.
Future landscapes		
Scenario 1	Drivers	- Existing driver remain; - Decreasing cost; - More big companies, who are able to afford training cost.
	barriers	- No new barriers identified.
	Evolvement	Rise.
Scenario 2 and 3	Drivers	- Existing driver remain; - Decreasing cost;
	Barriers	- Demand for safety training is reduced due to the less onsite workers; - AI has taken over the safety planning works.
	Evolvement	Still be used in safety training, the scale of which is limited on a very small scale. Decrease in the safety planning field because AIs have taken over the safety planning works.

Table F.11 The evolvements of AR in different scenarios

Augmented reality			
Working principle	Superimpose the hazard zones visionally on the real environment using AR devices, thereby helping the onsite workers to avoid the potential hazards.		
Current application	Technically possible, but very few attempts.		
	Drivers	-	Demand for a method to visualize the hazards information so that the onsite workers could avoid the potential hazards;
	Barriers	-	A bit expensive, but the price is decreasing.
		-	Some technical issues still need to be overcome.
Future landscapes			
Scenario 1	Drivers	-	Existing driver remains;
		-	Decreasing cost;
		-	Technical progress is being made;
		-	More big companies, who are able to afford the cost of devices.
	barriers	-	No new barriers identified.
	Evolvement	Rise.	
Scenario 2 and 3	Drivers	-	Existing driver remain;
		-	Decreasing cost;
	Barriers	-	Demand for safety training is reduced due to the less onsite workers.
	Evolvement	Rise, but the scale of the application will be limited.	

Table F.12 The evolvements of BIM in different scenarios

BIM			
Working principle	Provide hazards information to alarm the onsite workers; support other safety technologies, for instance, provide spatial models to VR devices to construct the digital environment for training.		
Current application	Have been employed to assist the safety management.		
	Drivers	-	The demand of integrating and managing the information related to construction safety.
	Barriers	-	Lack of imagination.
Future landscapes			
Scenario 1, 2 and 3	Drivers	-	Existing driver remains;
		-	The wide use of BIM in the construction industry provides great opportunities that BIM could be employed in the safety management.
	barriers	-	No new barriers identified.
	Evolvement	Rise	

Table F.13 The evolvements of VP in different scenarios

Virtual Prototyping			
Working principle	Simulate the construction process, to check the possible omissions in safety planning stage.		
Current application	Some similar simulations exist, but in safety management not yet.		
	Drivers	-	Demands for overviews of all potential risks in construction processes before actual starting to enhance the safety management.
	Barriers	-	Conservative and unawareness;
		-	No related legal requirements.
Future landscapes			
Scenario 1, 2 and 3	Drivers	-	Existing driver remain;
		-	Good performance of VP in safety-improving tests;
		-	The wide use of BIM in the future.
	barriers	-	No new barriers identified.
	Evolvement	Rise.	

Table F.14 The evolvements of wireless sensing in different scenarios

Wireless sensing			
Working principle	Track the objects (including both the equipment, workers, and building materials) to monitor their location in real time, thus pre-alarm and avoid potential collisions.		
Current application	Has been used, and is increasing.		
	Drivers	-	Avoid collision and related casualties, as well as financial loss.
	Barriers	-	No barriers identified.
Future landscapes			
Scenario 1	Drivers	-	Existing driver remain;
		-	More big companies, who are willing to pay for the extra cost of simulation.
	barriers	-	No new barriers identified.
	Evolvement	Rise.	
Scenario 2 and 3	Drivers	-	Existing driver remain;
	Barriers	-	Onsite workers are much less, the importance of casualty-preventing is lowered.
	Evolvement	Rise, but more focus on collision between objects to avoid financial loss and time waste.	

Table F.15 The evolvements of gesture monitoring system in different scenarios

Monitoring and big data			
Working principle	Monitor human workers' posters, and compare the pattern with the database, to identify the potential hazards and the risks of MSDs.		
Current application	A few trials have been made, but still not widely used.		
	Drivers	-	The demand of identifying the uncommon patterns in onsite workers' gestures to reveal the possible hazards and the risks of MSDs.
	Barriers	-	New method which people do not know well;
		-	Technical issues to be fixed;
		-	High initial cost.
Future landscapes			
Scenario 1	Drivers	-	The existing driver remains.
	barriers	-	No new barriers identified.
	Evolvement	May rise, but depends on the technical and financial feasibility of the technology in the future.	
Scenario 2 and 3	Drivers	-	Existing driver remain;
	Barriers	-	Reduced onsite workers lead to the very limited demand for onsite posture monitoring.
	Evolvement	It is used to assist the safety management work. However, for small contractors, it is not financially feasible to keep inhouse capability of gesture monitoring. They probably will choose to purchase service on market.	