Computers in Industry 83 (2016) 121–139

Contents lists available at ScienceDirect

Computers in Industry

journal homepage: www.elsevier.com/locate/compind

Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry

Thuy Duong Oesterreich*, Frank Teuteberg

Osnabrück University, Accounting and Information Systems, Katharinenstr. 1, 49074 Osnabrück, Germany

ARTICLE INFO

Article history:
Received 17 March 2016
Received in revised form 23 July 2016
Accepted 28 September 2016
Available online 5 October 2016

Keywords:
Industry 4.0
Systematic literature review
Case study research
Content analysis
PESTEL framework
Research agenda
Construction industry

ABSTRACT

In recent years, Industry 4.0 has been introduced as a popular term to describe the trend towards digitisation and automation of the manufacturing environment. Despite its potential benefits in terms of improvements in productivity and quality, this concept has not gained much attention in the construction industry. This development is founded in the fact that the far-reaching implications of the increasingly digitised and automated manufacturing environment are still widely unknown. Against this backdrop, the primary objective of this paper is to explore the state of the art as well as the state of practice of Industry 4.0 relating technologies in the construction industry by pointing out the political, economic, social, technological, environmental and legal implications of its adoption. In this context, we present the results of our triangulation approach, which consists of a comprehensive systematic literature review and case study research, by illustrating a PESTEL framework and a value chain model. Additionally, we provide recommendations for further research within a research agenda.

Contents

* Corresponding author.
E-mail addresses: toesterreich@uni-osnabrueck.de (T.D. Oesterreich), frank.teuteberg@uni-osnabrueck.de (F. Teuteberg).

http://dx.doi.org/10.1016/j.compind.2016.09.006
0166-3615/

1. Introduction and motivation

Nowadays, the visionary idea of Industry 4.0 or other synonyms like Smart Manufacturing, Smart Production or Industrial Internet, to name a few, have been promoted steadily by different actors to describe the trend towards digitisation, automation and the increasing use of ICT in the manufacturing environment. As a result, funding programs and research initiatives are raised by the government of several countries as part of their effort to gain or maintain global leadership in the manufacturing industries [1,pp. 69–70]. In this context, the term Industry 4.0 comprises a variety of technologies to enable the development of a digital and automated manufacturing environment as well as the digitisation of the value chain [2,3]. This results in improvements in product quality and a decrease of time-to-market as well as improvements in enterprise performance [4].

Despite the provided benefits, companies from the construction industry have not managed to integrate these innovative technologies to keep up with their counterparts from the automotive or mechanical engineering sector [5]. However, there exist many challenges specific to the construction industry that must be taken into account. For example, the entire construction value chain is highly affected by tight collaborations with customers, subcontractors and other stakeholders. Hence, construction projects are site-based, complex and individual undertakings which require a higher level of specialist knowledge. Furthermore, the construction industry sector consists of a high amount of small and medium-sized enterprises with limited capabilities for investments in new technologies [5].

As stated so far, the lack of innovation and technological progress in the construction industry is going hand in hand with the underinvestment for research and development (R&D). According to the 2015 EU R&D Scoreboard, the construction & materials industry is amongst the lowest R&D intensity sectors with less than 1% of net sales [6,p. 9]. These findings are surprising, judging from the fact that the construction industry is one of the major contributors to employment and economy of each country [5]. Given these circumstances, there is definitely a need for further research, as construction companies are facing increasing challenges through globally economic competition, resulting in thin profit margins and limited R&D investments [5]. In this context, the following research questions arise:

- Research question 1: Which technologies are currently associated with the concept of Industry 4.0 in the construction industry?
- Research question 2: What is the current state of the art of these technologies in the construction industry?
- Research question 3: Which technologies have already been adopted by companies of the construction industry in the recent years?
- Research question 4: Which far-reaching implications does the digitisation and automation of the construction environment entail for future research?

Based on these questions, the primary objective of this article is to fill a gap in literature by providing a comprehensive overview of the currently researched and adopted Industry 4.0 relating technologies in the specific environment of the construction industry. The remainder of this paper is organized as follows. The multifaceted concept of Industry 4.0 and the economic impact of the construction industry are presented in Section 2. In Section 3, we use a triangulation approach for data collection in order to provide comprehensive results. First, we intend to derive a definition of Industry 4.0 for construction in Section 3.1 by carrying out a systematic literature review and applying a content analysis. Subsequently, we build on this derived definition to identify scientific and practical literature and to explore the state of the art in Section 3.2. Additionally, we perform a case study research by using multiple case studies for the purpose of exploring the state of practice in construction companies in Section 3.3. Section 4 contains the results from the systematic literature review as well as the results from the case study research, resulting in a data triangulation and the development of a research agenda in Section 5. Finally, conclusions and a final outlook will be provided in Section 6.

2. Industry 4.0 in the construction industry

Recently, Industry 4.0 is being introduced as a popular term to describe the trend for the increasing use of information and automation technologies in the manufacturing environment [1,p. 76]. To clarify this term at the outset, we present the following definition prior to starting the analysis. Subsequently, we describe the impact of the construction industry as a part of nation's economy.

2.1. The concept of Industry 4.0

In comparison to many other traditional manufacturing concepts like Advanced Manufacturing or Lean Production which has been widely established in the scientific literature, Industry 4.0 can be identified as a term which is mainly used in the popular science in different contexts [4]. Developed by the German Federal Government to promote its High-tech strategy, this multifaceted term comprises a variety of interdisciplinary concepts without a clear distinction [2]. It has often been used as a synonym for the planned 4th Industrial Revolution by pointing out its huge technological potential, comparable to technical innovations which led to the first industrial revolutions: (1) the field of mechanisation, (2) the use of electricity and (3) the beginning of digitisation [2].

From the technical point of view, Industry 4.0 can be described as the increasing digitisation and automation of the manufacturing environment as well as the creation of a digital value chain to enable the communication between products and their environment and business partners [2,3]. As a result, simultaneous planning of products and production processes leads to improvements in product quality and decrease time-to-market [4]. As recommended by [1,pp. 31–32], the following key features are required for the implementation of Industry 4.0:

- Horizontal integration through value networks: The integration of IT systems, processes and data flows between different companies, e.g. customers, suppliers and other external partners enables closer collaboration with value chain partners across company borders.
- End-to-end digital integration of engineering across the entire value chain for the purpose of facilitating highly customized products, resulting in a reduction of internal operating costs. Therefore, a digital integration of the value chain by using cyber-physical systems is required.
- Vertical integration and networked manufacturing systems: Integration of IT systems, processes and data flows within the company from Product Development to Manufacturing, Logistics and Sales for cross functional collaboration, resulting in a smart manufacturing environment.

Beside these key aspects, there are several important enabling factors for the adoption to be considered, such as Internet of Things and Services, Big Data and Cloud Computing.

2.2. Specific characteristics and economic impact of the construction industry

The major role of the construction industry as one of the most important industries can be briefly addressed by providing the amount of investments in construction or its contribution to the GDP of each country. With a total construction investment amounted to 1.37 trillion Euro in 2014, the EU is one of the biggest market player in the construction industry, including Germany as its leading market, followed by France, the UK and Spain. According to the construction investment, the contribution of the mentioned markets is about between 9% and 12% of total GDP [7,p. 10].

Compared to the economic impact of the construction industry, investments in research and development (R&D) in this sector are relative low [5]. In 2015, the EU R&D Scoreboard has ranked industry sectors by their research and development intensity, comprising the 2500 companies investing largest sums in R&D in the world as well as an additional number of the top 1000 R&D investing companies based in the EU. In this Scoreboard, the construction industry is amongst the lowest R&D intensity sectors with less than 1% of net sales [6,p. 9]. This significant underinvestment for R&D is counter to the economic impact of the construction industry as one of the most important industry sectors. Another fact is that labour productivity in construction has declined over the last decades, while other manufacturing industries have nearly doubled its productivity in the same time [8,9]. Given these circumstances, it becomes clear that there are a number of structural problems within the construction industry that might be responsible for this mismatch:

- *Complexity*: Construction projects are complex undertakings due to the high amount of interrelated processes, sub-processes and the high number of project participants involved (architect, contractor, subcontractors, customer, suppliers) at different stages and locations [10,11].
- *Uncertainty*: As each construction project is a time-limited, site-based unique undertaking, there exists a lack of complete specification for processes and sub-processes and uniformity of materials, work and teams at construction site, resulting in an unpredictable environment [10].
- *Fragmented supply chain*: Another industry specific characteristic is the high fragmentation in the supply chain in terms of a high amount of small and medium size firms with undifferentiated products and services [11] and limited capabilities for investments in new technologies [5].
- *Short-term thinking*: The structure of the construction industry has been described by [10] as a loosely coupled system with tight couplings in individual projects and loose couplings in the permanent network, which supports short-term thinking but hampers long-term innovation and learning. Hence, the decentralised organisation of the construction companies as well as the temporary nature of the construction projects is a barrier to innovation.
- *Culture*: The construction industry is well-known for its strong and rigid culture as well as its strong resistance to changes [11].

3. Research methods

For the purpose of answering the research questions (RQ 1 – 4) posed in the motivation section, we decide to apply a combined research design which will be conducted step-by-step (Fig. 1).

To answer RQ 1, we focus on deriving a concept list containing a definition of the term Industry 4.0 by performing a systematic literature review and a qualitative and quantitative content analysis. To answer RQ 2, we conduct a second systematic literature review based on the derived concept list to explore the state of the art of the identified technologies. Subsequently, practical insights are provided by adding a case study research for answering RQ 3. In the last step, implications of the increasingly digitised and automated manufacturing environment will be presented within a PESTEL-framework and a research agenda to answer RQ 4.

3.1. Systematic literature review

The systematic literature review is recommended as a suitable method for the summarising of existing knowledge as well as

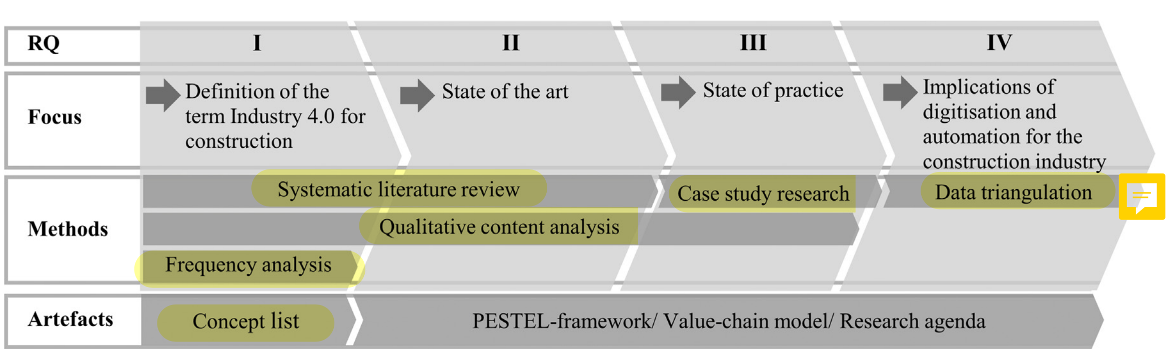

Fig. 1. Research design.

identifying and highlighting research gaps [12,13]. In our paper, we apply this method to identify and analyse scientific and practical literature by using the guidelines for IS systematic literature reviews recommended by [12]. To answer RQ 1 and RQ 2, the systematic literature review has to be carried out in 2 successive steps.

3.1.1. Systematic literature review, step 1

In the first step, we search for literature about the topic Industry 4.0 with a special focus on the construction domain. In doing so, we aim to build a solid base of data for the subsequent content analysis, which enables us to derive an industry specific definition for this term. For the first search in various scholarly databases, we use the German phrase Industrie 4.0" in combination with 'Bauindustrie', "Bauwirtschaft" or "Baubranche" as well as the English phrase Industry 4.0" in combination with Construction Industry" in order to cover both German and English publications. As our efforts end without results, it becomes clear that scientific publications still do not exist in this domain. Hence, we decide to broaden our search by performing a Google search as well as a search in Google Scholar with the same key phrases. The small number of 40 relevant publications confirm that Industry 4.0 has not gained much attention in the construction industry until now. Further statistical results as well as the results of the subsequent content analysis will be presented in Section 4.2. Besides, the detailed search results can be accessed on http://bit.ly/Appendix_COMIND (Appendix 1).

3.1.2. Systematic literature review, step 2

The second systematic literature review has to be conducted based on the concept list from the first systematic literature review and the subsequent content analysis. As mentioned before, the term Industry 4.0 comprises a variety of interdisciplinary concepts without a clear distinction [2]. Hence, at this point our purpose is to investigate the state of the art of all technologies which are considered as key technologies for Industry 4.0 adoption. During the search process of our second systematic literature review, we search for publications in research journals by accessing 5 interdisciplinary databases ScienceDirect, Emerald, Wiley Online Library, EBSCO Host and Ingentaconnect as well as practical publications by performing an open Google search. In doing so, we intend to comprise publications from all domains to get a comprehensive overview of the state of the art. Furthermore, as we aim to get an overview of articles concerning to the current use of all technologies, we focus on seeking for only recent articles published since 2010. A list of the detailed search phrases for the database and the Google search can be accessed via http://bit.ly/Appendix_COMIND (Appendix 2).

3.2. Scientific publications

Based on these key phrases, our search for scientific publications results in a total amount of 396 hits. In the second step of assessing relevance, we evaluate the content of the articles by reading the title as well as analysing the abstract. In doing so, we decide to exclude articles which only focus on mechanical or technical aspects of the civil engineering discipline. After the evaluation and selection process, 149 articles remain. Following the plea for more rigour and transparency during the search process [12,13], we provide an overview of the applied search criteria, filters and the detailed search results in the Appendix via http://bit.ly/Appendix_COMIND (Appendix 3).

3.3. Practical publications

As expected, our Google search for practical publications results in a high amount of hits. At this point it is worth mentioning that our main objective of this open search does not lie in providing a complete overview of all relevant results, but rather in the providing of additional information about the current state of the art of the investigated technologies. Thus, we only go through the first 10 results pages, relying on the assumption that the search results of the first pages can be considered as the most relevant ones [14]. The detailed results of our second systematic literature review will be presented in Section 4.3. Again, the detailed search results can be seen on http://bit.ly/Appendix_COMIND (Appendix 4).

3.4. Qualitative and quantitative content analysis

The method of content analysis can be described as "a systematic, replicable technique for compressing many words of text into fewer content categories based on explicit rules of coding" [15]. It is being considered as useful in dealing with large volumes of data for examining trends and patterns in documents. As we aim to investigate patterns in Industry 4.0 literature about the definition of this term, this method can help us to analyse the collected data. Therefore, we combine the qualitative content analysis for a category oriented text interpretation [16] and the frequency analysis for a statistic-based text interpretation [17] to benefit from the strength of both methods. Within the qualitative content analysis, we follow recommendations delivered by Mayring's step model as follows [16]:

- Formulation of the research question
- Coding agenda: Definition of the aspects of analysis, main categories, sub categories and formulation of definitions, examples and coding rules for the categories
- Revision of categories and coding agenda, formative check of reliability
- Final work through the texts, summative check of reliability
- Interpretation of the results, if necessary: quantitative steps of analysis (frequency analysis)

For the frequency analysis [18], the following procedure in Fig. 2 has to be considered in order to analyse the collected data using the software QDA Miner [19] and its extension WordStat [20].

The results of our software-aided content analysis is provided in Section 4.2 as the first artefact of the overall investigation.

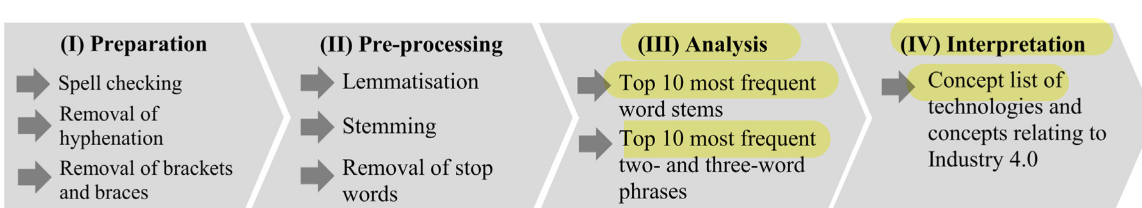

Fig. 2. Procedure for frequency analysis (based on [18,21]).

3.5. Case study research

To complement the findings from the scientific and practical literature, we additionally conduct a case study research in order to investigate the state of practice of the identified technologies in construction companies to answer RQ 3. Case study research has been described as a well-suited qualitative research method to the IS-discipline, since it aims to examine the contemporary phenomena within the natural settings by employing multiple methods of data collection [22]. Besides, it is appropriate for complementing the research results by addressing practitioner's experiences. Moreover, this method is also considered suitable for areas in which research and theory are at their early stage of development. During the investigation, we follow a framework recommended by [23]:

3.5.1. Area 1 – design issues

Based on the concept list in Section 4.2, our case study research is focused on companies of the construction industry, following the multiple-case design for the purpose of cross-casing analysis [22].

3.5.2. Area 2 – data collection

The process of data collection is performed by an open Google search in full text, using the keywords ("Construction Industry" OR "Construction Company") AND ("Case study" OR "Use Case") in combination with the same key phrases applied in the second systematic literature review section (Appendix 2 on http://bit.ly/Appendix_COMIND). Additionally; we use the date-range filter to get results dating from 2010 onwards. Within the selection and evaluation process; we decide to include case studies which focus on the application in construction companies and exclude those which only contain technical issues without practical experiences. A high amount of promotional materials which are extremely focused on promotion issues have also been excluded. Finally; we select 9 case studies from multiple kind of sources; e.g. reports (documents containing information about specific use cases; published by external organisations or companies); promotional materials (advertising documents containing information about products or services of an organisation) and research papers (publications containing original research results) to be further considered.

3.5.3. Area 3 – data analysis

The analysing process of the selected case studies will be performed in Section 4.4.

3.6. Method and data triangulation

Originally used for navigation and military strategy, triangulation has been adopted as a research strategy in the social sciences [24]. Basically, triangulation offers to researchers the opportunity of viewing and analysing the research topic from different perspectives. As a result, the research questions can be better answered because researchers can put together the different findings from the various methods and produce more consistent and convergent results. In this article, we use method and data triangulation in order to combine results of our systematic literature review with the results of our multiple case analysis from the case study research section. The process of data triangulation will be presented in Section 4.4.

4. Results

In the following sections, we start by providing related work and pointing out the uniqueness of our contribution. Subsequently, we present the results from our systematic literature review as well as the findings from the case study research. Finally, we merge the results by using the "within-method" for the purpose of data triangulation.

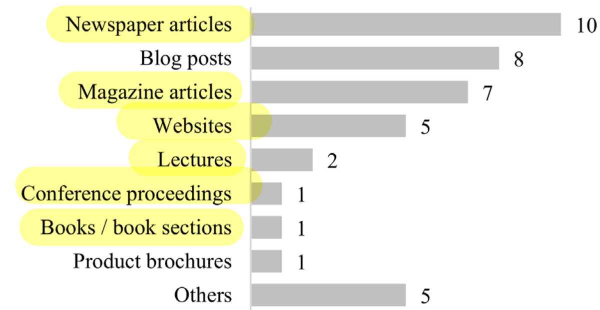

Fig. 3. Types of publication for qualitative and quantitative content analysis (n = 40).

4.1. Related work

To identify related work, we perform a Google Scholar search with the key phrases "Literature review" AND ("Industry 4.0" OR "Industrie 4.0") and use the date range filter to get results dating from 2010 onwards. After evaluating the results, we decide to consider 3 articles as related work [4,25,26]. The results reveal that only a few peer-reviewed articles have been published which contain a systematic literature review for Industry 4.0. Another notable finding is the small number of cites of all Industry 4.0 contributions, comparing to other well researched topics from the IS discipline. For example, one of the articles [4] is listed in Harzing's Publish or Perish-Ranking[1] on the 4th place of all Industry 4.0 articles with only 51 cites since 2014, while other articles count 10 times more cites in the same time, e.g. articles with the topic "data mining". A more detailed overview of the related works can be accessed via http://bit.ly/Appendix_COMIND (Appendix 5). In essence, all of the 3 relating articles are aiming to provide a definition of the term Industry 4.0 as well as its key technologies and concepts from a technical point of view. A contribution with deeper insights into the state of the art and state of practice in a specific industry sector has not been published until now. Hence, to the best of our knowledge, our contribution is the first one to provide key concepts of Industry 4.0 in the specific context of the construction industry.

4.2. Results of the content analysis: Industry 4.0 definition for construction

Taking into consideration that there exists no clear definition for Industry 4.0, we attempt to derive an understanding for this term with a special focus on the potential use in the construction environment. As can be seen from Fig. 3, most of the 40 investigated publications are newspaper articles, magazine articles, blog posts or websites. A detailed overview of all publications is presented on http://bit.ly/Appendix_COMIND (Appendix 6).

As already expected, research papers are not among them. Considering these statistics, we can assume that the topic Industry 4.0 has mainly attracted strong media attention in the construction industry, while research efforts or best practices are not

[1] http://www.harzing.com/pop.htm.

Table 1
Industry 4.0 technologies and concepts in practical publications (n = 40).

Technologies and concepts (Practical publications)	Number of publications
Building Information Modelling (BIM)	28
Internet of Things (IoT)/Internet of Services (IoS)	12
Product-Lifecycle-Management (PLM)	11
Cloud Computing	10
Mobile Computing	10
Augmented Reality (AR)/Virtual Reality (VR)/Mixed Reality (MR)	9
Robotics	9
Radio-Frequency Identification (RFID)	8
Big Data	7
3D-Printing/Additive Manufacturing	5
Smart Factory	4
Human-Computer-Interaction (HCI)	3
Modularisation	3
Cyber-Physical Systems (CPS)/Embedded systems	2

widespread yet. One consideration should be kept in mind when analysing these statistics: Although we have searched for English publications during the first systematic literature review as well, only 3 relevant hits have been identified. Granted, this finding is not surprising, as it is a well-known fact that this research field is still in its formative years, especially in construction. In the next step, we aim to figure out which technologies and concepts are considered as part of Industry 4.0 in the identified publications in order to compare these findings with the results from the Industry 4.0 literature (Tables 1 and 2).

The results of the qualitative content analysis show that Building Information Modelling (BIM) is considered as the central technology for the digitisation of the construction manufacturing environment, as it has been mentioned in 28 of the investigated practical publications (Table 1). This result is consistent with the statistical findings from the top 10 most cited Industry 4.0 literature, as simulation and modelling has been described as one of the most relevant concepts to manage the growing complexity of manufacturing processes and to improve them by setting scenarios and reducing risks in the early stages of the production [1,pp. 42–43]. Among the other associated technologies and concepts are well-known manufacturing concepts like Product-Lifecycle-Management (PLM), Modularisation and Robotics as well as information and communication technologies like Mobile Computing and Radio-Frequency Identification (RFID) as one of the key technologies for Cyber-Physical Systems. Typical base technologies and concepts of Industry 4.0 are the Internet of Things (IoT)/Internet of Services (IoS), Cloud Computing, Big Data, Smart Factory, 3D-Printing and the Cyber-Physical Systems (CPS) or Embedded systems. Also, Augmented Reality (AR)/Virtual Reality (VR)/Mixed Reality (MR) and the Human-Computer-Interaction (HCI) are major components of Industry 4.0 to enable a digitised construction environment.

The results from our frequency analysis confirm the major role of BIM as one of the most important technologies in construction. According to Tables 3 and 4, BIM is by far the most frequent word stem in the investigated publications, followed by word stems describing the features of BIM as a digital planning method, such like PLAN, DIGITAL and MODEL. The German word stems INDUSTRI, TECHNI, DATEN (data) and UNTERNEHMEN (company) outline the importance of Industry 4.0 for construction companies, while CLOUD and SYSTEM are used to describe base technologies for BIM adoption or digitisation in general.

As can be seen in Table 4, the INDUSTRIE 4.0, INDUSTRY 4.0 and the synonym BAUEN 4.0 (German term for Construction 4.0) are the most frequent bigrams. This is not surprising, due to the fact that we are investigating publications with a focus on the topic Industry 4.0.

Again, BUILDING INFORMATION MODELING and CLOUD COMPUTING are among the top 10 most frequent bigrams and trigrams. Other technologies like BIG DATA and the German term INTERNET DER DINGE (Internet of Things) are also frequently used phrases. The phrases WERTSCHÖPFUNGSKETTE BAU (construction value chain) and FÜR KMU (for SME) show the major impact of

Table 2
Industry 4.0 technologies and concepts in top 10 most cited Industry 4.0 publications (n = 10).

Technologies and concepts (Industry 4.0 literature)	Number of publications
Cyber-Physical Systems (CPS)/Embedded systems	10
Internet of Things (IoT)/Internet of Services (IoS)	8
Radio-Frequency Identification (RFID)	8
Robotics	6
Big Data	6
Cloud Computing	6
Simulation and Modelling	6
Smart Factory	6
Human-Computer-Interaction (HCI)	5
Modularisation	5
Product-Lifecycle-Management (PLM)	5
Augmented Reality (AR)/Virtual Reality (VR)/Mixed Reality (MR)	4
3D-Printing/Additive Manufacturing	3
Mobile Computing	3
Social Media	3

Table 3
Top 10 most frequent word stems (unigrams).

#	Word stem	Frequency
1	BIM	472
2	PLAN	287
3	INDUSTRI	251
4	TECHNI	199
5	DIGITAL	166
6	CLOUD	159
7	SYSTEM	158
8	DATEN	153
9	MODEL	147
10	UNTERNEHMEN	141

Table 4
Top 10 two- and three-word phrases (bigrams and trigrams).

#	Two- and three-word phrases (Bigrams and trigrams)	Frequency
1	INDUSTRIE 4.0	94
2	BUILDING INFORMATION MODELING	51
3	INDUSTRY 4.0	40
4	CLOUD COMPUTING	25
5	BAUEN 4.0	14
6	WERTSCHÖPFUNGSKETTE BAU	14
7	BIG DATA	13
8	FÜR KMU	13
9	INTERNET DER DINGE	12
10	ÖFFENTLICHE HAND	11

digitisation on the construction value chain as well as the potential benefits for the small and medium enterprises (SME), while the phrase ÖFFENTLICHE HAND (public sector) has often been used to describe the high expectations towards government mandates and initiatives. Comparing to the listed concepts in Table 1, several technologies of this concept list are not among the most frequent unigrams, bigrams or trigrams, although they have been coded as base technologies during the qualitative content analysis. The reason for this discrepancy is the fact that several technologies have occured in the coded text as different terms. For example, the coded category Mobile Computing has been mentioned in the investigated publications as "Mobile Endgeräte" (mobile devices), "Smartphones", "Tablets" and "Mobiles Arbeiten" (mobile working), German and English terms to describe the use of Mobile Computing.

To answer RQ 1 based on the results from our content analysis, the industry specific definition of Industry 4.0 for construction

	Types of publication	Number of publications
Scientific publications	Journal articles	146
	Conference proceedings	3
Practical publications	Blog posts	63
	Magazine articles	26
	Conference proceedings	9
	Reports	6
	Newspaper articles	5
	Books/ book sections	2
	Product brochures	2
	Others	6
	Total	**268**

Fig. 4. Types of the identified publications.

comprises a wide range of interdisciplinary technologies and concepts which enables the digitisation, automation and integration of the construction process at different stages. In some cases, Industry 4.0 is used as a synonym to describe the increasing use of ICT and other manufacturing technologies, but contains no further specification.

However, we group the identified technologies, concepts, synonyms and terms into 3 main clusters and 16 concepts to build a concept list (Table 5). Based on this list in Table 5, we provide the results of the second systematic literature review to outline the current state of the art in Section 4.3.

4.3. State of the art

4.3.1. Statistical results

The next step of our systematic literature review is dedicated to the analysis of the identified scientific and practical publications to provide the state of the art of Industry 4.0 relating technologies. Fig. 4 gives an overview of all relevant publications, clustered by their type of publication. From this figure it can be seen that the base of data for the ongoing investigation comprises a wide range of scientific publications like peer-reviewed journal articles as well as practical publications like blog posts, magazine articles or reports. Although the majority of the practical publications are not peer-reviewed and thus may be considered as opinion-driven and biased, we decide to include them to complement and validate the research-based literature review [27].

Table 5
Concept list.

Cluster	Key technologies and concepts in the context of Industry 4.0
Smart Factory (C1)	Cyber-Physical systems/Embedded systems/RFID
	Internet of Things/Internet of Services
	Automation
	Modularisation/Prefabrication
	Additive Manufacturing
	Product-Lifecycle-Management (PLM)
	Robotics
	Human-Computer Interaction (HCI)
Simulation and modelling (C2)	Simulation tools/Simulation models
	Building Information Modelling
	Augmented Reality (AR)/Virtual Reality (VR)/Mixed Reality (MR)
Digitisation and virtualisation (C3)	Cloud Computing
	Big Data
	Mobile Computing
	Social Media
	Digitisation

Rank	Country	Scientific publications Adjusted #	Scientific publications Adjusted %	Practical publications Adjusted #	Practical publications Adjusted %	Total Adjusted #	Total Adjusted %
1	USA	32.1	21.5%	64.0	53.8%	96.1	35.9%
2	UK	8.6	5.8%	18.0	15.1%	26.6	9.9%
3	China / Hongkong	19.7	13.2%	1.0	0.8%	20.7	7.7%
4	Canada	15.7	10.5%	3.0	2.5%	18.7	7.0%
5	Australia	7.8	5.2%	7.0	5.9%	14.8	5.5%
6	Korea	12.3	8.2%	2.0	1.7%	14.3	5.3%
7	Germany	4.8	3.2%	3.0	2.5%	7.8	2.9%
8	Malaysia	3.3	2.2%	3.0	2.5%	6.3	2.3%
9	Sweden	3.0	2.0%	2.0	1.7%	5.0	1.9%
10	Taiwan	4.8	3.2%		0.0%	4.8	1.8%

Fig. 5. Adjusted percentage of the top 10 countries.

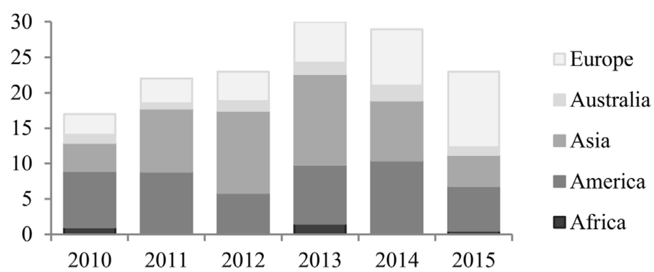

Fig. 6. Distribution of the investigated articles by year and continent.

For the analysed articles of our systematic literature review, we identify authors from 44 countries and 5 continents. For the purpose of summarising the statistical results, we present the top 10 countries in Fig. 5 by addressing the adjusted percentage of the articles for each country. The determination method of the adjusted number of articles as well as a detailed example is provided on http://bit.ly/Appendix_COMIND (Appendix 8).

With a share of 36%, the USA is the major contributor of all publications, followed by the UK and China. Besides, the statistics show that the majority of all practical publications stem from the USA and the UK with a share of nearly 70%, while China as a main contributor to scientific publications is only responsible for 1% of all practical publications.

According to Fig. 6, the distribution of the investigated articles by year and continent indicates that America's and Australia's contribution to research and practice in this field remains stable, while the number of articles from Asian countries have declined over the last 2 years. At the same time, the contributions from European countries have increased impressively.

Taking into account the statistical data based on the investigated publications, we can sum up that the leaders in construction research and practice stem from the USA, the UK or China, while Germany is only on 7th rank. This overall finding does not mean that the German construction industry is less innovative than the

Cluster	Key technologies and concepts in the context of Industry 4.0	Number of relevant scientific publications	Number of relevant practical publications
Smart Factory (C1)	Cyber-Physical systems (CPS)/ Embedded systems	2	0
	Radio-Frequency Identification (RFID)	11	6
	Internet of Things (IoT)/ Internet of Services (IoS)	0	27
	Automation	21	3
	Modularisation/ Prefabrication	7	4
	Additive Manufacturing	0	8
	Product-Lifecycle-Management (PLM)	2	3
	Robotics	6	13
	Human-Computer Interaction (HCI)	2	1
Simulation and modelling (C2)	Simulation tools/ Simulation models	55	1
	Building Information Modelling (BIM)	30	11
	Augmented/Virtual/Mixed Reality (AR/VR/MR)	18	13
Digitisation and virtualisation (C3)	Cloud Computing	6	5
	Big Data	0	9
	Mobile Computing	2	1
	Social Media	3	6
	Digitisation	4	8
	Total	**169**	**119**

Fig. 7. Summary of the concept matrix.

construction industry of other countries, but it indicates that digitisation and automation has not been focused by German researchers and practitioners until now.

For the analysis and synthesis of the relevant publications, we use the concept-centric approach of the concept matrix [13]. Therefore, we group both scientific and practical publications in 3 main clusters and 17 concepts. However, it is worth mentioning that there exist overlaps between the defined clusters, as several of the relevant articles could be assigned to more than one cluster. Hence, a number of 20 articles are assigned to different concepts and clusters. For example, if an article deals with Mobile Computing and Human-Computer Interaction, it is being grouped in both concepts.

Fig. 7 presents the summary of the concept matrix by pointing out the statistical results of the investigated scientific and practical publications. A more detailed concept matrix including all 268 references can be accessed via http://bit.ly/Appendix_COMIND (Appendix 7).

4.3.2. Qualitative results

Cluster 1: Smart Factory

The first cluster (C1) in Fig. 7 comprises a wide range of technologies and concepts to automate the construction process and to create a “Smart Factory” for the construction environment. The corresponding technologies of this cluster fit to the “End-to-end digital integration of engineering” which is described as one of the key features of Industry 4.0 by [1,pp. 31–32]. In general, there are a few interesting approaches to create a “smart construction site”.

For example, [28] deals with the integration of *Cyber-Physical-Systems (CPS)* for the purpose of facilitating bi-directional coordination between virtual models and physical construction, including the validation of the developed proof-of-concept prototype systems by industry practitioners. Another approach for the application of CPS as part of a real time monitoring system to check the use of personal protective equipment (PPE) during the construction activities is presented by [29]. The integration of the hardware like RFID tags, RFID reader and other devices in the worker’s suit enables the real-time tracking of the PPE in order to control that the workers are wearing them.

As far as sensor technology is concerned, *Radio-Frequency Identification (RFID)* offers manifold solutions for the *automation* of the construction process. It enables site personnel to effectively track and manage their assets like tools, equipments, materials and prefabricated building components for the purpose of optimising project schedule and project cost [30]. Besides, it can also be applied for inventory management and theft prevention, since the embedded sensors can act as a recovery tool to locate stolen equipment or to act like a deterrent [31]. Safety and workforce management are other application scenarios on construction sites. In practice, RFID is being used for access control to avoid site access by unauthorized personnel and to track the number and identities of workers on construction sites [31]. Despite its benefits, a widespread use of RFID in construction has not taken place [32].

Another central concept in cluster 1 is the *Internet of Things and Services (IoT and IoS)*, which enables the creation of virtual networks to support a smart factory environment [1,p. 14]. From the technical point of view, the IoT is described as a combination of sensors like RFID, other communication devices, cloud applications, ERP integration and business intelligence technology [33]. The sensors are embedded in physical objects, such as vehicles and heavy equipments (cranes, dozers, loaders), machines, robotics or building components with the ability to connect to the Internet. To benefit from IoT technology, machines and equipments can send performance data to engineers to be analysed. In doing so, the construction industry can move away from reactive maintenance, where machines and equipments run until failure before they get repaired. Based on the performance data, predictive maintenance can help to reduce costs by predicting failure points and allowing engineers to repair the machines and equipment before damage occurs [34]. According to a recent report by McKinsey&Company, IoT technology can save $160 billion to $930 billion annually on construction sites and other work sites such as mines [35]. However, this technology has not been adopted by construction companies. Notably, no research efforts can be identified in this domain. Among the practical publications, there are many articles to promote the benefits of the IoT without real use cases.

Looking to the future, *Additive Manufacturing* is a technology which enables the automate manufacturing of the most complex architectural components without extra labour costs. Based on a digital model, the 3D-printing of buildings or components is technically achieved by laying down layer upon layers of material until the entire object is formed [36]. In recent years, the field of Additive Manufacturing is affected by a high level of progressive research [37]. Today, the maturity of this technology is considered on a level where full sized testing based on prototypes can be accomplished [38]. Although 3D printed homes are being offered for the commercial use [39], a widespread application of this technology in construction is being expected for 2020 onwards [36].

Modularisation as another concept of Industry 4.0 is technically known as prefabricated construction. It refers to the manufacturing of larger building components away from construction site which are mostly fabricated in a factory and then transported to the construction site, where they are assembled by using cranes [40]. Prefabrication has already been widely adopted in construction companies [41], as it offers great benefits to enhancing quality and safety while reducing waste and costs [40].

Robotics are also mentioned to support the vision of the smart factory [1,p. 20]. Despite the fact that it can make construction work easier, safer, more efficient and more attractive [42], only a few approaches have been proposed to use robotics technology on construction site, e.g. robotic automation of the steel beam assembly to replace human workers [43]. Recently, various kinds of autonomous robotics have been developed to support construction work. For example, a commercial bricklaying robot has recently been presented to build an entire house in 2 days [44]. Other robots can sort through construction waste to seek for recyclable materials, removing asbestos or finish concrete floors [45]. Furthermore, drones are being deployed by a few construction companies for surveying and capturing images for providing progress reports, jobsite surveillance, monitoring deliveries or providing the eyes for automated bulldozers by sending a 3D model of the building site to a computer which then instructs the unmanned machinery to plot its course [46]. Although it is well-known as a main part of the manufacturing assembly concept, e.g. for the automotive sector, robotics technology has not been widely represented in construction research and practice. This fact is understandable, as the low level of standardisation in the construction process and the harsh construction environment does not provide an ideal environment for robotics [47].

Product-Lifecycle-Management (PLM) is a concept which deals with the seamless integration of all information produced throughout all phases of the whole lifecycle of a company’s product [48]. Although the concept of PLM is widely well-known and established, it is being considered as key element to enable a digital value chain. In practice, PLM is often linked with Building Information Modelling and has even been used as synonyms to describe a seamless digital model of a product for a better collaboration [49].

The last concept of cluster 1 deals with articles from the concept of Human-Computer Interaction (HCI). They are focused on several aspects concerning to the increasing use of ICT, for example the investigation of the influencing factors for successful implementation of mobile computing by using the Technology Acceptance Model [50], or the development of a framework for identifying and understanding the factors of individual acceptance and use of ICT [51]. In many cases, the way humans interact with technology, e.g. with robotics, is considered as the main key to implementing a successful solution on construction site [52].

Cluster 2: Simulation and modelling

Cluster 2 (C2) deals with simulation and modelling, another central part of Industry 4.0. As construction projects are unique and highly complex undertakings which are influenced by external factors like weather, worker performance and supply fluctuations, simulation can be applied to improve the design of construction operations [53]. Hence, most research articles from cluster 2 offer a wide range of *simulation-tools, simulation-models* or frameworks for project planning, resource planning or project management in general. Among them, there exists a high number of articles dealing with Virtual Reality (VR) to create a risk-free virtual learning and training environment, e.g. for construction safety training [54]. Also, the use of Augmented Reality (AR) is being treated in several articles, e.g. for supporting defect management in combination with BIM [55] or real-time communication on-site [56]. In practice, the field of Augmented Reality (AR), Virtual Reality and Mixed Reality (MR) is still at the formative stage, as applications for the use on construction site are still being developed. For example, a Mixed Reality (MR) application is being presented by Trimble and Microsoft using the HoloLens and 3D modelling technology to enable users to interact with 3D holograms blended into the real world. The interaction of the user by using gesture, gaze and voice provides the opportunity for project participants to explore the 3D model for improving communication, collaboration and customer relationship [57]. Besides, many solutions are currently available, offering a variety of applications for the use with mobile devices or wearable computing to enhance safety on construction sites [58]. For example, the hard hat "Daqri Smart Helmet" has been proposed to aid construction workers on site by displaying 3D visual overlays in the wearer's field of vision [59]. Other applications based on the use of Smart Glasses have also been offered for enabling instruction manuals or remote support in hands-free mode [60].

Among the articles from cluster 2 (C2), a high amount of scientific and practical publications are identified as contributions to the emerging field of Building Information Modelling (BIM). As shown in Fig. 8, the number of the publications for BIM has steadily increased since 2012. This development is supposed to be continued in the coming years, as many countries are starting to attach greater priority to the benefits providing through BIM. For example, German's government has lately announced its plan for the introduction of BIM for the planning and realisation of large-scale infrastructure projects with the purpose of making BIM mandatory for these projects from 2020 onwards [61].

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,

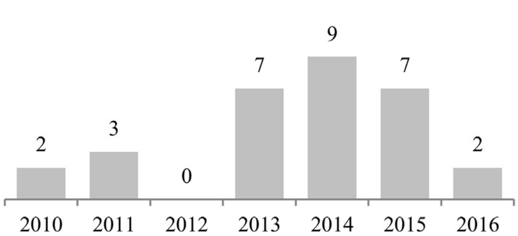

Fig. 8. Distribution of BIM articles by year.

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 throughout the whole lifecycle of the building [62]. According to the Industry 4.0 concept, the idea of the digital value chain as well as the cross-company collaboration is being presented by [1,pp. 31–32] as the end-to-end engineering across the entire value chain and horizontal integration through value networks. Thus, BIM can be considered as one of the central technologies to support the main idea of Industry 4.0.

Digital collaboration based on BIM is treated in several articles. For example, [63] presents a case study of successful BIM collaboration by pointing out the relevance of the key enabling factors: Technical aspects like a cloud computing infrastructure, BIM contracts and BIM learning environment as well as other factors like change agents for the implementation of new roles and responsibilities. According to BIM adoption and implementation in the construction domain, the USA, the UK and the Scandinavian region are considered as global leaders, as their governments have heavily invested in national funding programs, BIM mandates, implementation plans and incentives [64]. To reap its full benefits, the adoption of BIM has to be accompanied by the use of other base technologies like Cloud Computing, Mobile Computing and the digitisation of information flows within the company [65].

Cluster 3: Digitisation and virtualisation

To continue the analysis of the relevant publications, cluster 3 (C3) contains articles relating to digitisation and virtualisation technologies. Among them, *Cloud Computing* is responsible for the provision of integrated services with the opportunity to be accessed via the Internet, e.g. for cross-company collaboration on construction site. Most publications are not focused on providing Cloud Computing solutions as a major topic, but rather as part of the whole concept, e.g. as key enabling technology for BIM [63], for project management applications, payroll solutions, ERP systems or digital document management platforms to create a "single source of truth" for the project team [66]. The use of cloud-based solutions enables all project participants to access information from any communication device with Internet access, e.g. over a file-sharing collaboration platform for viewing, managing, distributing, and collaborating on construction documents in real time [67].

Finally, as the huge amounts of data have to be managed, the implementation of *Big Data* solutions can help 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 [68]. For instance, the analysis of historical big data (e.g. 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 [69]. Due to the fact that no scientific publications have been identified during the search process of our systematic literature review, Big Data analytics seems to be an application-driven topic in construction.

Another central concept of cluster 3 is *Mobile Computing*, which refers to the use of mobile devices to support communication and collaboration during the construction process. Despite the growing interest in using mobile devices in the construction industry [50], there are only a few contributions toward this topic. One explanation for this is the fact that Mobile Computing is already widespread in construction, due to the high amount of available mobile devices, applications and solutions. According to the 2015 Construction Technology Report, 97,6% of construction professionals surveyed use a smartphone and 69,4% of them use a tablet for work purposes [70].

Table 6
Concept matrix for case studies.

Cluster	Key technologies and concepts	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
C1	Automation						x		x	
	Modularisation/Prefabrication			x						
	Product-Lifecycle-Management (PLM)		x	x						
C2	Simulation tools/Simulation models			x						
	Building Information Modelling (BIM)		x			x		x		x
	Augmented Reality (AR)/Virtual Reality (VR)/Mixed Reality (MR)			x						
C3	Cloud Computing				x	x		x		
	Mobile Computing		x	x	x	x		x		
	Social Media					x				
	Digitisation	x		x		x				x

Social media usage has been mentioned in Industry 4.0 literature as an effective way to improve the production process [71,p. 60]. Particularly, social media can be considered as suitable for the construction industry, as its fragmented structure with the high amount of different project participants requires a common platform as a network for connecting, interacting and information sharing. For example, a BIM-based social platform for knowledge management has been proposed to enable project-related discussions, to provide visualisations to project stakeholders and thus to create tacit knowledge [72]. Besides, social media is an effective method to improve recruitment, project management and client networking [73]. Social media apps like the interactive blueprint app "PlanGrid" provides the opportunity for project teams to view, share, annotate and sync blueprints on tablets and in the cloud and thus to make communications easier between on-site and off-site teams [74]. Despite the benefits social media offers, the construction industry lags behind most other industries in terms of social media usage [73]. The last category of cluster 3 is *digitisation*, a term which is mostly used in order to describe the trend towards the extensive use of ICT to create a digital value chain. The articles which we grouped into this concept are focused on digital project data and information management or digitisation in general.

In summary, the analysed articles of our systematic literature review are mostly dealing with technical aspects of Industry 4.0 relating technologies. Social, ethical or legal questions are addressed by only a few of them. Furthermore, a holistic approach for the implementation or utilisation of the Industry 4.0 concept in the construction environment has not been treated at all. According to RQ 2, the state of the art of the investigated technologies and concepts are on different levels of maturity. Nonetheless, a variety of solutions are being offered to digitise and automate the construction process and to achieve substantial improvements in construction productivity.

4.4. Case study analysis

Overall, the small number of 9 relevant case studies underlines the assumption that the construction industry is lagging behind other industry sectors in terms of digitisation and automation. However, there exist a few interesting case studies for the utilisation of Industry 4.0 relating technologies. A summarised overview of the treated technologies and concepts is being presented in Table 6.

As opposed to the statistical findings from the systematic literature review, the major role of simulation and modelling for the use in construction companies cannot be clearly confirmed by considering the results of the case studies. Interestingly, the most applied technologies are concepts from Cluster 3, comprising Cloud Computing, Mobile Computing, Social Media and digitisation (Table 7).

As shown in Fig. 9, the selected case studies comprise a wide range of different companies from the construction industry, e.g. small and medium-sized enterprises (SME) like John McCall's Architects or Russells Construction, but also large enterprises like Laing O'Rourke or Walsh Construction[2].

Remarkably, most companies are headquartered in the USA and the UK. Besides, there are no Asian companies among them. This finding correlates to the statistical results from the systematic literature review presented in Fig. 5, which underlines the major role of the USA and the UK as the main contributors to practical publications. The key figures were collected from the case studies, the annual reports of each company or from the information published on their websites.

To present the key findings of the case studies, we summarise the contents by pointing out the key questions and the main focus. The cases are sorted by company size (number of employees).

To answer RQ 3, the overall insights of the case study analysis reveal that companies from the construction industry have already begun to digitise and automate their construction processes. At this point it is important to keep in mind that the provided cases are not representative for the whole construction industry. They can rather be considered as best practices to demonstrate that there are many ways to transform the construction business in a practical way.

4.5. Implications of digitisation and automation for the construction industry

Retrospectively, the major findings of our systematic literature review and case study analysis confirm that several digitisation and automation technologies for construction have reached market maturity and thus are currently available. The adoption of these technologies are going hand in hand with several implications for the whole industry, the involved companies, the environment and for people. On the one hand, construction companies can gain from many benefits. Table 8 summarises these benefits named in the investigated publications by grouping them in 6 perspectives using the PESTEL-framework [83,p. 48]. The perspectives are: political (P), economic (E), social (S), technological (T), environmental (E) and legal (L). In doing so, we intend to summarise and combine the findings of our systematic literature review with the findings of our multiple case analysis from the previous sections.

On the other hand, there are manifold challenges and unsolved problems that must be taken into account prior to the digital transformation of the industry (Table 9). These challenges have been described in Industry 4.0 literature and the investigated scientific and practical publications as well.

[2] According to http://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Enterprise_size.

Table 7
Summary of the case studies.

Case 1	CEMEX (Mexico)
Publication	Promotional material [75]
Company profile	Global building materials company (concrete, cement and aggregates)
Key question	How to handle an IT transformation process from a business unit oriented to an end-to-end business processes approach?
Main focus	• Redesign and implementation of an integrated business model and an end-to-end horizontal business process approach with focus on a business-driven approach • IT transformation process from a business unit oriented to an end-to-end business processes approach • Creating capability for the use of other innovative technologies like mobile apps, social networks, cloud services and business analytics
Case 2	The Royal BAM Group (The Netherlands)
Publication	Report [76]
Company profile	European construction group
Key question	(1) How to enable multidisciplinary collaboration during the whole building's lifecycle? (2) How to improve the sustainability of the buildings through the use of BIM?
Main focus	• Utilisation of BIM for design and project management across a building's lifecycle and for multidisciplinary collaboration. • Utilisation of BIM as key driver for improving the sustainability rating of a building: (1) Creating design alternatives (2) Optimising building solution (3) Offering a variety of different solutions which might fit best to customer's needs • Benefits for end-user and customers: (1) Transparency in terms of the building's performance at operational level (energy, carbon, cost savings and user experience) (2) Customer can see what the building will look like before the building is finished • Utilisation of BIM during the maintenance stage of a building by planning the maintenance visits through easy access to the stored equipment data of the BIM model
Case 3	Laing O'Rourke (UK)
Publication	Report [77]
Company profile	Global construction group
Key question	How to deliver an integrated approach of digital engineering?
Main focus	• Implementation of a digital engineering approach including the utilisation of digital models to integrate design information, data and documentation throughout the project's lifecycle • Modular onsite-assembly of components manufactured off-site • Use of Augmented Reality and mobile devices for a clearer understanding of the model and a better progress monitoring • Automated generation of reports and charts through integrated information. • Capturing knowledge for increasing predictability of project outcomes and for more transparency (safety, design, cost, schedule and quality)
Case 4	Walsh Construction (USA)
Publication	Promotional material [78]
Company profile	General contracting, construction management and design-build company
Key question	How to link the growing demand for mobility with the increasing need for data security to enable enhanced collaboration?
Main focus	• People-centric approach for the use of Mobile Computing and Cloud Computing to enable access to cloud and applications via iPhones and iPads • Use of identity federation within the Cloud to help quickly and securely share data and collaborate with external businesses, e.g., sharing elements of the enterprise resource planning solution with contractors for cost reporting
Case 5	DPR Construction (USA)
Publication	Report [79]
Company profile	Building contractor and construction managing company
Key question	How to drive technological innovation by involving company's own employees?
Main focus	• Approach of work environment redesign and innovation driven by the own workforce of the company, e.g. by investigating innovative practices across all industries globally and applying them to the company • Focus on interdisciplinary collaboration and engagement in idea sharing and dialogue: (1) Implementation of a cloud storage technology to access drawings and blueprints from mobile devices for enabling a real-time update and better information sharing as well as reducing the volume of paper drawings (2) Implementation of computers with large screens for viewing and reworking on complex 3D modelling and drawings (3) Development of a company-wide library of 3D virtual mock-ups for knowledge sharing and knowledge reusing (4) Utilisation of BIM for better design and better-coordinated construction process
Case 6	Crossland Construction (USA)
Publication	Promotional material [80]
Company profile	General contracting construction company
Key question	How to automate the tracking of employee time on site to enhance control of labour costs, improve compliance and increase productivity?
Main focus	• Implementation of an automated workforce management solution for automated capturing of employee time at biometric terminals • Enhancing transparency for employees through easy access to time information and accrual balances at the time clock and online • Enhancing control of labour costs and improving compliance
Case 7	Devcon (USA)
Publication	Promotional material [81]

Company profile	General contracting construction company
Key question	How to handle the lack of access to high-bandwidth connectivity to enable data exchange and collaboration?
Main focus	• Delivering virtualised services to remote sites by using a cloud-based SD-WAN for a reliable access to cloud apps and improving remote collaboration and mobility • Utilisation of a cloud-based BIM management and collaboration environment for connecting project teams and streamlining BIM project workflows from pre-construction phase through construction execution phase (1) Easy access of large blueprints and project plans on tablets (2) Enabling the opportunity for video collaboration (3) Time and cost saving in deploying and managing remote sites
Case 8	Russells Construction (UK)
Publication	Promotional material [82]
Company profile	Construction company
Key question	How to create an integrated, networked system to manage staff and contractor data for enhancing security on site?
Main focus	• Implementation of an automated system for access control in combination with an integrated and networked system to log and manage staff and contractor data on site (1) Using biometric access control pads and entrance portacabins for allowing site access for permanent staff and contractors through hand print recognition (2) Availability of collected data to monitor staff and contractor timesheets (3) Enhancing security on construction site.
Case 9	John McCall's Architects (UK)
Publication	Research paper [11]
Company profile	Architecture and construction services
Key question	How to achieve a successful implementation of BIM?
Main focus	• BIM adoption with focus on the successful implementation from a technical and socio-cultural perspective by using a combination of human-centered, information and process driven system implementation strategies: (1) Soft system methodology: 7 steps of SSM for business process modelling, problem solving and managing change (2) Information engineering, predominantly data driven: Arrangement of the data in a structured framework, storage in a database for better data access (3) Business Process Redesign • 5 stages provided for the BIM implementation process: (1) Identification and analysis of current practices, e.g. current processes, current ICT systems within the company (2) Identification of efficiency gains from BIM implementation (3) Process Redesign and technology adoption path • BIM implementation, staff training, process integration and documentation (1) Project review, sustaining, evaluation and dissemination for continuous improvement

Taking into consideration all these manifold challenges in research and practice, it becomes clear that the construction industry has to embrace more than technological changes. From a scientific point of view, the provided benefits and challenges can be considered as research topics to be further investigated and as questions to be answered within a further research agenda. From a managerial point of view, they can be used as a framework to be considered prior to the digital transformation of the company. In any case, there is an urgent need for further research in the

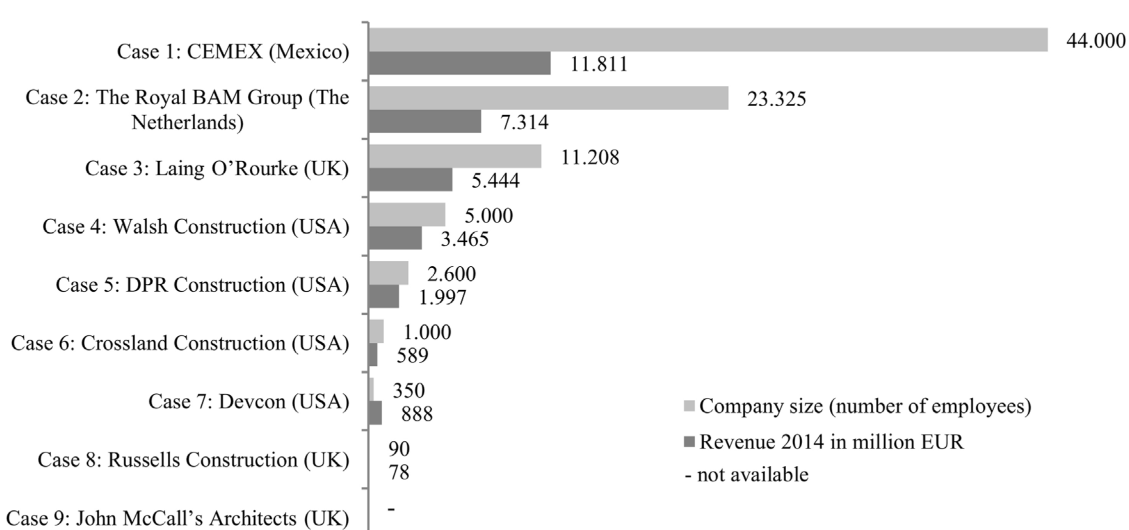

Fig. 9. Key figures of the companies of the case studies.

Table 8
Benefits of Industry 4.0 for the construction industry.

	Perspective					
Implications I: Benefits	P	E	S	T	E	L
• ***Cost savings:*** The automation of labour-intensive processes, e.g. through the use of robotics or automated workflows results in a reduction of labour costs [52]. Additionally, the automated tracking of equipments and materials by using embedded sensors can help to reduce material costs [30].		x				
• ***Time savings:*** Innovative manufacturing technologies and concepts like Prefabrication or Additive Manufacturing enable the construction of buildings in matter of days, faster than conventional construction methods [36], [41].						
• ***On-time and on-budget delivery:*** In the past, delivery of construction projects on time and on budget has been proven to be a challenging task. The use of BIM can help to decrease project delivery time and keep projects under budget [58].		x				
• ***Improving quality*:** The use of BIM and other simulation technologies has been mentioned to increase the quality of the building, as errors can be avoided in the early stages by simulating the whole construction process [84]. Furthermore, Big Data analytics can help project managers to make more effective and well-informed decision based on historical data [68].		x				
• ***Improving collaboration and communication:*** Due to the high amount of project participants involved in each construction project, cloud- and BIM-based platforms or social media apps can efficiently improve collaboration and communication even across company borders [63], [66].		x				
• ***Improving customer relationship***: By applying simulation technologies like Augmented Reality, Virtual Reality and Mixed Reality in combination with mobile devices or wearable computing, construction companies are able to provide project owners greater insights into the details and design of a building before it is built [58]. Thus, customers can be involved in the planning process for a better customisation of the building.		x				
• ***Enhancing safety:*** The high number of articles for safety management reveals that safety is one of the most important issues in construction. Due to its hazardous work environment, the construction industry is well known for its high rate of work injuries and accidents [54], Accordingly, many different approaches are presented by researchers and practitioners to improve construction safety, e.g. through virtual safety training [85], using risk maps for avoiding work accidents [86] or using wearable technologies like Smart Glasses or Smart Helmets [87].			x			
• ***Improving the image of the industry:*** The construction industry is well known for its harsh working environment and its low level of digitisation. Thus, it is suffering from a poor employer image and often struggles to attract talented recruits to their workforce. The digital transformation of the whole industry can help to improve its image [88].			x			
• ***Improving sustainability:*** The building and construction sector is responsible for high carbon dioxide emissions, caused by its energy consumption and high level of waste during its construction processes [89]. In order to handle these environmental problems, several approaches have been proposed for construction waste minimisation [90], for reducing project emissions through strategic project management [91] or for using BIM to create design alternatives [76].					x	

construction domain. The impact of the investigated technologies on the construction value chain is illustrated in Fig. 10.

Due to the specific characteristics of the construction industry as well as the complex nature of the construction projects, the key features of the Industry 4.0 concept are presented as 3 dimensions within the value chain model:

(1) Horizontal integration through value networks as the result of the increasing number of project participants involved in the whole value chain (contractor, customer, architect, designer, subcontractors, suppliers): In large-scale construction projects, there might be hundreds of different project participants involved. Thus, the use of Industry 4.0 technologies from cluster 2 and cluster 3 can help to create a suitable construction environment for enhanced collaboration and communication, e.g. through the use of a centralised cloud-based collaboration environment [78] in combination with the use of Building Information Modelling [81], Mobile Computing and Augmented Reality [77].
(2) End-to-end digital integration of engineering across the entire value chain through the use of technologies from all clusters, e.g. Building Information Modelling [11], Cyber-Physical Systems [28] and Mobile Computing [78] to deliver an integrated approach of digital engineering during all stages of the construction project (Tendering, briefing, design, plan, construct and use & maintain).
(3) Vertical integration and networked manufacturing systems as the result of the integration of IT systems, processes and data flows within the company through the use of digitisation and virtualisation technologies (cluster 3) [75] or the integration of automation technologies (cluster 1) [80], [82].

Overall, Industry 4.0 can help construction companies to reduce complexity and uncertainty, to enhance information exchange and communication between project stakeholders and thus to increase productivity and quality.

5. Elements of a research agenda

Notwithstanding the apparent hype around Industry 4.0 and its economic benefits, there is still a lack of research for the potential use of its technologies [3] and the implications for society, companies, people and processes. Hence, the primary aim of the first phase of our proposed research agenda in Fig. 11 is to investigate the state of the art and state of practice by applying a systematic literature review and a multiple case analysis in this paper.

Two considerations should be kept in mind when interpreting the results of this paper. First, as we have only investigated research papers, practical publications and case studies published in English and from the year 2010 onwards, we cannot guarantee to have covered all relevant publications. Hence, the results of this research are limited to a selected number of publications and should be validated by further studies, e.g. expert interviews or empirical study. Second, the selected practical publications and case studies are non-peer-reviewed publications like blog-posts, magazine articles and promotional materials containing information which cannot be verified.

However, the major findings reveal that current research streams are mainly focused on investigating technical aspects of Industry 4.0 relating technologies. Economical, socio-cultural, ethical or environmental questions remain widely unconsidered. For instance, an adequate cost-benefit analysis for the estimating of the implementation and utilisation costs and the benefits has

Table 9
Challenges of Industry 4.0 for the construction industry.

	Perspective					
Implications II: Challenges	P	E	S	T	E	L
• ***Hesitation to adopt:*** Due to the high investment costs of new technologies and the unclear benefits, construction companies are hesitating to invest in them [64]. Thus, one of the main challenges is to motivate construction companies for the adoption of new technologies, e.g. by providing incentives for the adoption [30], through government mandates for BIM use [64], [76], and through funding programs for industry and research [1, p. 37]	x					
• ***High implementation cost:*** As already mentioned, the high cost for technical equipment [28], for training and education [28], [30] and for external consultancy fees [64] are a barrier to adoption. Unclear benefits and prediction of cost savings [76] and a lack of consistent fiscal benchmarking to evaluate the business improvements and gains [11] are other unsolved problems. In this context, the development of methods and tools for estimating and optimising costs and benefits [30] and the provision of industry association partnerships to work together [64] can help to increase transparency and to reduce costs.		x				
• ***Organisational and process changes:*** The implementation of new technologies must take place at all levels of the organisation [51] and mostly requires the re-evaluation and re-engineering of business practices [11], [64], [75], [92]. For construction companies, the main question to be answered is how to successfully handle the organisational and process changes within the organisation and how to redesign the current business model [11], [75].		x				
• Need for enhanced skills: The use of new technologies requires a certain level of knowledge. Due to the low technical competency of the construction workers on site [28], [30], there will be an increasing need for staff training and development [11], [64], [84] as well as the increasing need for integration skills [77], [92]. Hence, the big challenge is to create and develop new competencies, to optimise the project organisation and to attract new talents to the workforce, like staff with shared technical knowledge and integration experience as key selection criteria. Additionally, companies should encourage employees to collaborate and engage idea sharing for creating innovation [79] and therefore create opportunities for interdisciplinary groups to collaborate and elevate performance [79].			x			
• ***Knowledge management:*** The temporary nature of the construction projects and the fragmented characteristics of the construction value chain are reasons for the lack of codified and shared project knowledge [92] and limited standards for knowledge management [92]. The main challenge is to create and establish standards for knowledge management within the organisation. This can be achieved by capturing and reusing of project knowledge [92] and through automated data collection and embedding into project history [92]			x			
• ***Acceptance:*** The construction industry is known for its strong resistance to changes and new technologies [30] as well as the conservatism and inability to adapt by staff members of its companies [64]. Furthermore, one of the major concerns of employees about the adoption of new technologies is the job-loss, as they might be replaced by machines, computers or robotics [93]. In any case, communication and change management for helping employees to adapt is required [75], since acceptance is a critical success factor for the adoption of new technologies. Thus, companies can involve change agents as "opinion leaders" during the implementation process [63] and implement leading ideas of employees to help them feel ownership over performance improvement [79].			x			
• ***Lack of standards and reference architectures:*** Despite the current maturity and availability of most technologies, there exists a lack of standards for many of them, e.g. a lack of complete and international standard for RFID technology and multi-protocol tags and readers [30], or a lack of consistent BIM standards (software incompatibility) [64]. Furthermore, there is a need for an industry-specific reference architecture for Industry 4.0 [2]. With regard to the specific environment of the construction industry, this reference architecture has to be developed with a special focus on its structure (e.g. site-based projects, high number of small and medium sized companies involved).				x		
• ***Higher requirements for computing equipment:*** As construction projects are highly affected by external factors like weather, traffic and its surroundings, higher requirements for computing equipment for the use in the specific construction site environment (mostly outdoors, dust and moisture) have to be taken into account [94]. For example, mobile devices should be designed to handle strong vibrations, large falls and humidity.				x		
• ***Data security and data protection:*** The growing data volumes, the increasing demand for mobility, collaboration and sharing information with external partners, e.g. by applying the BYOD-approach (bring your own device) [78] results in an increasing need for data security and data protection [80], [82]. Companies should protect their data against unauthorized access and any kind of misuse through centralised cloud-based user-identity, access management, device management and data protection tools [78].				x		
• ***Enhancement of existing communication networks:*** The use of information and communication technologies requires a fast and reliable Internet access on construction sites. Hence, unreliable broadband connectivity [81] or the lack of access to high-bandwidth connectivity for collaboration applications [81] have been mentioned as one of the most important obstacles to be overcome.				x		
• ***Regulatory compliance:*** The use of RFID technology for safety management and workforce management requires the automated capture and record of personal data. In many cases, there exist ethical and legal concerns about the tracking and monitoring of employees as well as the handling of the recorded information [1,p. 60]. For example, according to German data protection law, high restrictions have to be considered in case of the outsourcing of corporate data containing personal information about employees to companies outside the European Union or European Economic Area. Prior to the implementation of these technologies, restrictions concerning to privacy and data protection have to be checked by involving legal experts right from the earliest stages of the process [1,p. 61].						x
• ***Legal and contractual uncertainty:*** Another obstacle is the legal and contractual uncertainty concerning to the use of BIM. For example, questions of the legal ownership of the model and the legal responsibility for errors and problems with the model have to be answered [64].						x

not been provided yet. As stated several times, construction companies are hesitating to adopt new technologies because of the high investments and uncertainty concerning to the resulting benefits [64,76]. Also, it remains unclear which implications the utilisation of Industry 4.0 entail for future job design in the construction companies and on construction site. These fundamental questions are only a few of many open questions for construction companies to be answered prior to the adoption of new technologies.

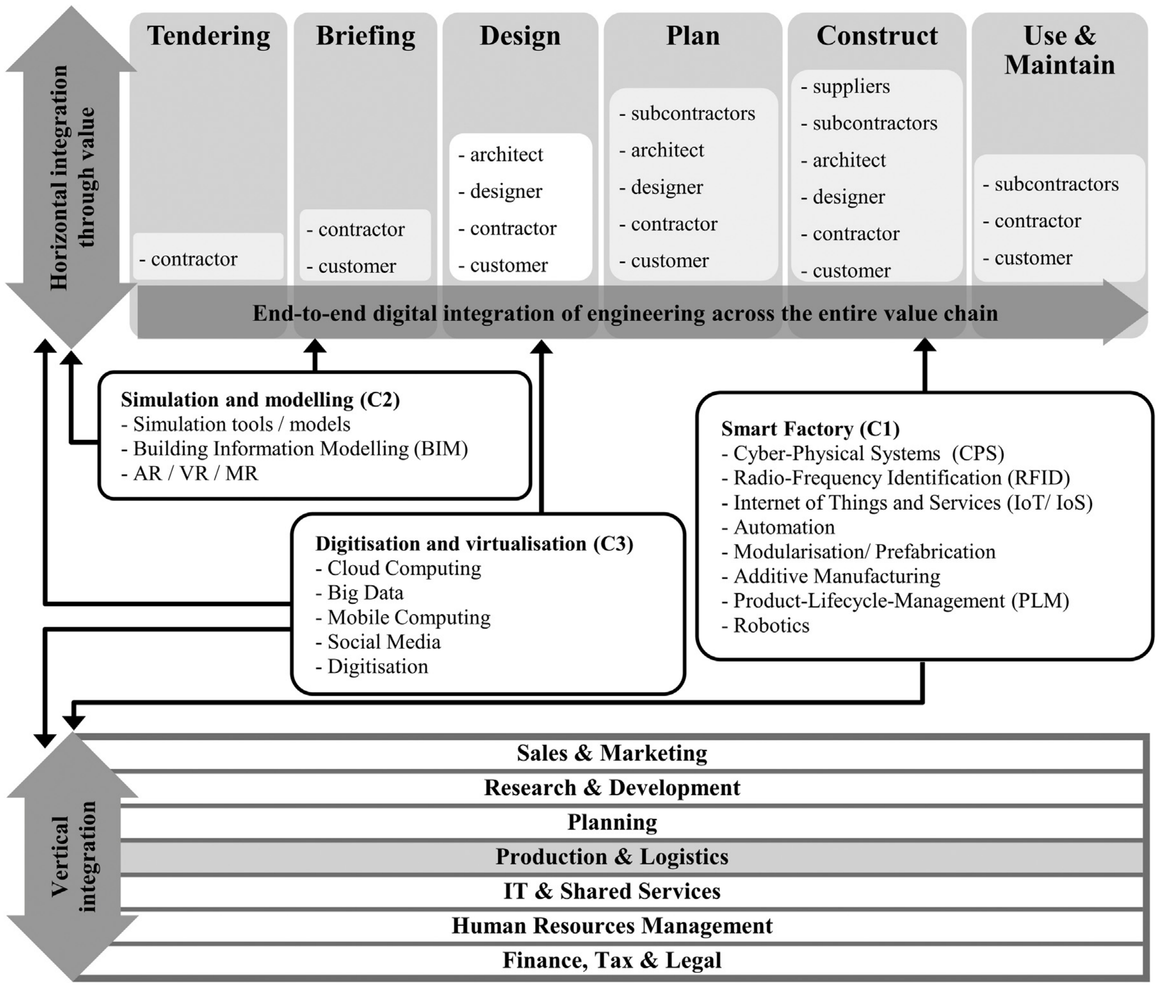

Fig. 10. Impact of Industry 4.0 technologies on the construction value chain (based on [95,p. 18]).

Against this backdrop, there does exist the urgent need for the development, understanding and assessment of frameworks, business models, reference models and maturity models for Industry 4.0 implementation with focus on technology, people and processes. For instance, one of the major tasks for future research is to investigate the key influencing factors for the successful implementation of Industry 4.0 in the construction environment and to enhance the understanding of these factors, e.g. the Industry 4.0 readiness of construction companies. Based on this enhanced understanding, a guideline for the successful implementation with

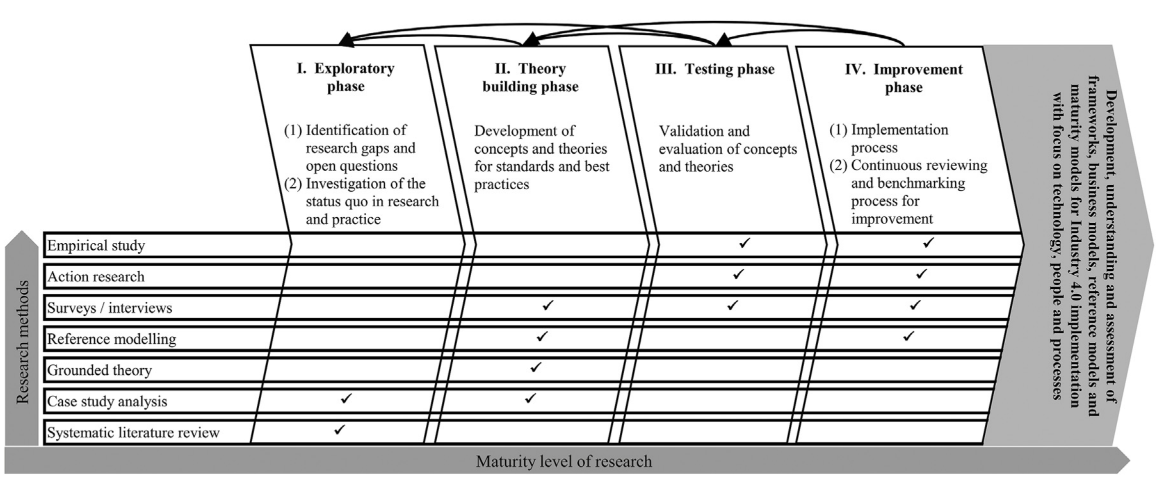

Fig. 11. Proposed research agenda for future research.

respect to the specific characteristics and requirements of the construction environment can be provided for companies to be considered prior to the implementation of new technologies.

The described step of developing concepts and theories is part of the theory building phase within the research agenda in Fig. 11. Within this phase, Grounded Theory is one of the well-suited methods for the development of concepts and theories for several reasons. First, this research method is considered as extremely useful in developing context-based, process-oriented descriptions and explanations of information systems phenomena [96]. Second, it is appropriate for developing theories of greater scope and in areas where prior knowledge of the research field does not lead to pre-formulated hypotheses, such as the area of Industry 4.0. Based on empirical data from surveys and interviews as well as qualitative findings from case studies, Grounded Theory can help to build up concepts and theories that are grounded in the collected data [96].

During the third phase of the research agenda, the developed concepts and theories have to be validated by applying action research, empirical study as well as surveys and interviews in order to find out if they are suited for the application in companies. After the implementation, the concepts have to be continuously reviewed and benchmarked for a continuous improvement.

6. Conclusion and outlook

In this article, the primary aim was to explore the current state of the art and state of practice of Industry 4.0 relating technologies in the construction industry and to provide the main implications concerning to the potential use from different perspectives. Based on the comprehensive outcome of our investigation, the following conclusions can be drawn:

- The industry specific definition of the Industry 4.0 concept for construction comprises a plethora of interdisciplinary technologies to enable the digitisation, automation and integration of the construction process at all stages of the construction value chain. Central technologies like Building Information Modelling (BIM), Cloud Computing or the Internet of Things are only a few of them.
- The state of the art of these technologies are on different levels of maturity. On the one hand, several technologies have reached market maturity and thus are currently available (e.g. BIM, Cloud Computing, Mobile Computing, Modularisation). On the other hand, a few technologies are still at the formative stage, as prototypes and applications are being developed for mainstream use (e.g. Additive Manufacturing, Augmented, Virtual and Mixed Reality).
- Despite the given maturity and availability of many technologies, their widespread adoption by construction companies has not taken place until now. However, there exist best practices which demonstrate that there are practical ways for the adoption of new technologies to digitise and automate the construction process.
- The adoption of Industry 4.0 technologies has far-reaching implications for the whole construction industry, the involved companies, the environment and for employees. Beside the economic benefits for improving productivity, efficiency, quality and collaboration, their adoption can help to enhance safety, sustainability and thus to improve the poor image of the construction industry in the long run. To fully reap these benefits, manifold political, economic, social, technological, environmental and legal challenges have to be embraced. For example, companies have to deal with organisational and process changes, with high implementation costs and the unclear prediction of cost savings or with the increasing need for data security and data protection. Employees have to handle with increasing job requirements and a higher level of mental stress due to the fear about job losses. From the technical point of view, there are several unsolved problems to be faced like the lack of standards for many technologies, the higher requirements for computing equipment or the increasing need for enhanced communication networks. Regulatory compliance, legal and contractual uncertainty are other issues to be taken into account. Considering these manifold challenges, it becomes clear that companies have to be motivated for the adoption through government mandates, initiatives or funding programs.

Nonetheless, the adoption of the Industry 4.0 concept can help the construction industry to transform to a technology-driven industry and to keep up with other manufacturing industries in terms of performance improvement. To move the innovative concept of Industry 4.0 in the complex environment of the construction industry towards new frontiers, further efforts in science and practice are needed. Future work should involve the challenges addressed and the example questions posed within the research agenda.

Acknowledgements

The authors would like to thank the anonymous reviewers for their very insightful and constructive comments which have substantially contributed to the improvement of this paper.

References

[1] H. Kagermann, W. Wahlster, and J. Helbig, Umsetzungsempfehlungen für das Zukunftsprojekt Industrie 4.0, acatech, Frankfurt/Main, Apr. 2013.
[2] H. Lasi, P. Fettke, H.-G. Kemper, T. Feld, M. Hoffmann, Industrie 4.0, Bus. Inf. Syst. Eng. 6 (4) (2014) 239–242.
[3] R. Schmidt, M. Möhring, R.-C. Härting, C. Reichstein, P. Neumaier, P. Jozinović, Industry 4. 0 – potentials for creating smart products: empirical research results, Bus. Infor. Syst. (2015) 27.
[4] M. Brettel, N. Friederichsen, M. Keller, M. Rosenberg, How virtualization, decentralization and network building change the manufacturing landscape: an industry 4. 0 perspective, Int. J. Mech. Aerosp. Ind. Mechatron. Manuf. Eng 8 (1) (2014).
[5] J.A. Kraatz, K.D. Hampson, A.X. Sanchez, The global construction industry and R&D, R&D Investment and Impact in the Global Construction Industry, 1st ed., Routledge, 2014, pp. 4–23.
[6] H. Hernández, F. Hervás Soriano, A. Tübke, A. Vezzani, M. Dosso, S. Amoroso, N. Grassano, A. Coad, P. Gkotsis, EU R&D SCOREBOARD. The Industrial R&D Investment Scoreboard, European Commission – Joint Research Centre, Luxembourg, 2015.
[7] Deloitte S.L., EPoC 2014. European Powers of Construction, Deloitte S.L., Madrid, Jun. 2014.
[8] P.M. Teicholz, Labor-productivity declines in the construction industry: causes and remedies (a second look), AECbytes 1 (67) (2013) (p. n/a).
[9] S. Changali, A. Mohammad, M. van Nieuwl, The Construction Productivity Imperative, July, McKinsey & Company, 2015.
[10] A. Dubois, L.-E. Gadde, The construction industry as a loosely coupled system: implications for productivity and innovation, Constr. Manag. Econ. 20 (October (7)) (2002) 621–631.
[11] Y. Arayici, P. Coates, A system engineering perspective to knowledge transfer: a case study approach of BIM adoption, in: T. Xinxing (Ed.), Virtual Reality – Human Computer Interaction, ed., InTech, 2012.
[12] J. vom Brocke, A. Simons, B. Niehaves, K. Reimer, Reconstructing the giant: on the importance of rigour in documenting the literature search process, Proceedings of the European Conference on Information Systems (ECIS) (2009) p14.
[13] J. Webster, R. Watson, Analyzing the past to prepare for the future: writing a literature review, Manag. Inf. Syst. Q. 26 (no. 2) (2002).
[14] Google Inc., How Google Search Works – Search Console Help, Search Console Help, 2016. [Online]. Available: https://support.google.com/webmasters/answer/70897?hl=en. (accessed: 21.05.16).
[15] S. Stemler, An overview of content analysis, Pract. Assess. Res. Eval. 7 (17) (2001).
[16] P. Mayring, Qualitative content analysis, JunForum Qual. Sozialforschung Forum Qual. Soc. Res. 1 (June (2)) (2000).
[17] B. Berelson, Content Analysis in Communication Research, Free Press, 1952.

[18] A. Sidorova, N. Evangelopoulos, J.S. Valacich, T. Ramakrishnan, Uncovering the intellectual core of the information systems discipline, MIS Q. 32 (3) (2008) 467–482.
[19] Provalis Research, QDA Miner 4. 2011.
[20] Provalis Research, WordStat 7. 2014.
[21] M. Walterbusch, M. Gräuler, and F. Teuteberg,How Trust is Defined: A Qualitative and Quantitative Analysis of Scientific Literature, AMCIS 2014 Proc., Jun. 2014.
[22] I. Benbasat, D.K. Goldstein, M. Mead, The case research strategy in studies of information systems, MIS Q. 11 (3) (1987) 369–386.
[23] L. Dubé, G. Paré, Rigor in information systems positivist case research: current practices, trends, and recommendations, MIS Q. 27 (Dezember (4)) (2003) 597–636.
[24] T.D. Jick, Mixing qualitative and quantitative methods: triangulation in action, Adm. Sci. Q. 24 (Dezember (6)) (1979) 602–611.
[25] M. Hermann, T. Pentek, and B. Otto, Design Principles for Industrie 4.0 Scenarios, Dortmund, Working paper, 2015.
[26] H.-C. Pfohl, B. Yahsi, T. Kurnaz, The impact of industry 4.0 on the supply chain, Innovations and Strategies for Logistics and Supply Chains, (2015) , pp. 31–58.
[27] K.M. Benzies, S. Premji, K.A. Hayden, K. Serrett, State-of-the-evidence reviews: advantages and challenges of including grey literature, Worldviews Evid. Based Nurs. 3 (June (2)) (2006) 55–61.
[28] A. Akanmu, C.J. Anumba, Cyber-physical systems integration of building information models and the physical construction, Eng. Constr. Archit. Manag. 22 (5) (2015) 516–535.
[29] S. Barro-Torres, T.M. Fernández-Caramés, H.J. Pérez-Iglesias, C.J. Escudero, Real-time personal protective equipment monitoring system, Comput. Commun. 36 (December (1)) (2012) 42–50.
[30] J. Majrouhi Sardroud, Influence of RFID technology on automated management of construction materials and components, Sci. Iran. 19 (3) (2012) 381–392.
[31] M. Roberti, How is RFID being used in the construction industry? Ask Experts Forum 6 (2013).
[32] J. Sequeira, Tracking your kit: How to use RFID technology on construction sites –Middle East Construction News, 29-Dec-2015.
[33] Whitelight group, How the Internet of Things is transforming construction. 18-Aug-2014.
[34] B. Thompson, Asset management critical for the growing, tech-driven construction industry, GenesisSolutions, 02-Sep-2015. [Online]. Available: http://www.genesissolutions.com/asset-management-critical-for-the-growing-tech-driven-construction-industry/. (accessed: 28.05.16)
[35] J. Manyika, M. Chui, P. Bisson, J. Woetzel, R. Dobbs, J. Bughin, D. Aharon, The Internet of Things: Mapping the Value Beyond the Hype, june, McKinsey&Company, 2015.
[36] S. Baynes and M. Steele, 3D Printing and the Construction Industry, Canada Mortgage and Housing Corporation (CMHC), 3, Dec. 2015.
[37] M. Fischer and V. Baznajac, A framework for bringing 3D printing into the construction industry, Stanford University – CIFE Center for Integrated Facility Engineering, Stanford, 2013–1, Jan. 2013.
[38] S. Wright, Impacts of 3D Printing on the Construction Industry, Contractors Equipment Directory, 05-May-2016.
[39] Winsun, 3D Printing Construction – English, 2016. [Online]. Available: http://www.yhbm.com/index.php?a=lists&c=index&catid=67&m=conten. (accessed: 07.06.16).
[40] J. Hong, G.Q. Shen, C. Mao, Z. Li, K. Li, Life-cycle energy analysis of prefabricated building components: an input?output-based hybrid model, J. Clean. Prod. 112 (January (4)) (2016) 2198–2207.
[41] McGraw Hill Construction, Prefabrication and Modularization: Increasing Productivity in the Construction Industry, McGraw Hill Construction, Survey, 2011.
[42] H. Son, C. Kim, H. Kim, S.H. Han, M.K. Kim, Trend analysis of research and development on automation and robotics technology in the construction industry, KSCE J. Civ. Eng. 14 (2) (2010) 131–139.
[43] K. Jung, B. Chu, D. Hong, Robot-based construction automation: an application to steel beam assembly (Part II), Autom. Constr. 32 (2013) 62–79.
[44] Fastbrick Robotics, Fastbrick Robotics, (2016) [Online]. Available: http://www.fbr.com.au/.(accessed: 07.06.16).
[45] KFMR, Robotics, Transforming the Construction Industry, february, (2013) [Online]. Available: http://www.kfmr.com/robotics-transforming-construction-industry. (accessed: 29.05.16).
[46] J. Wakefield, Tomorrow's Buildings: Construction industry goes robotic, BBC News, 05-Apr-2016. [Online]. Available: http://www.bbc.co.uk/news/technology-35746648. (accessed: 29.05.16).
[47] J.-K. Kajander, The robotic revolution in the construction industry? Nordic Constr. Innov. (April) (2016).
[48] R. Sudarsan, S.J. Fenves, R.D. Sriram, F. Wang, A product information modeling framework for product lifecycle management, Comput. Aided Des. 37 (13) (2005) 1399–1411.
[49] M. Day, Construction industry wary of collaboration Business Technology, Bus. Technol. (June) (2011).
[50] H. Son, Y. Park, C. Kim, J.-S. Chou, Toward an understanding of construction professionals' acceptance of mobile computing devices in South Korea: an extension of the technology acceptance model, Autom. Constr. 28 (December) (2012) 82–90.
[51] Z. Zakaria, S. Ismail, A.M. Yusof, Modelling the determinants influencing the need of computer simulation framework in improving the closing of final account in construction projects, Adv. Sci. Lett. 20 (January (1)) (2014) 321–325.
[52] D. Bruemmer, The automation of the construction industry, Constr. Bus. Owner Mag. (February) (2016).
[53] S. AbouRizk, D. Halpin, Y. Mohamed, U. Hermann, Research in modeling and simulation for improving construction engineering operations, J. Constr. Eng. Manag. 137 (10) (2011) 843–852.
[54] Chan King Chun, Heng Li, and Martin Skitmore, The use of virtual prototyping for hazard identification in the early design stage, Constr. Innov. 12 (1) (2012) 29–42.
[55] C.-S. Park, D.-Y. Lee, O.-S. Kwon, X. Wang, A framework for proactive construction defect management using BIM, augmented reality and ontology-based data collection template, Autom. Constr. 33 (2013) 61–71.
[56] X. Wang, P.E.D. Love, M.J. Kim, C.-S. Park, C.-P. Sing, L. Hou, A conceptual framework for integrating building information modeling with augmented reality, Autom. Constr. 34 (2013) 37–44.
[57] Trimble, Trimble and Microsoft HoloLens: The Next Generation of AEC-O Technology | Trimble Buildings, 2015. [Online]. Available: http://buildings.trimble.com/hololens. (accessed: 20.02.16).
[58] K. Jones, Five ways the construction industry will benefit from augmented reality LinkedIn pulse, LinkedIn Pulse (August) (2016).
[59] DAQRI, DAQRI Smart Helmet –DAQRI, 2016. [Online]. Available: http://daqri.com/home/product/daqri-smart-helmet/. (accessed: 08.06.16).
[60] Ubimax GmbH, Innovative Lösungen, Ubimax GmbH, 2016. [Online]. Available: http://www.ubimax.de. (accessed: 08.06.16).
[61] BMVI,, Building information modeling (BIM) wird bis 2020 stufenweise eingeführt, Informationen des BMVI (December) (2015) [Online]. Available: http://www.bmvi.de/SharedDocs/DE/Pressemitteilungen/2015/152-dobrindt-stufenplan-bim.html?nn=35712. (accessed: 30.12.15)..
[62] V. Popov, V. Juocevicius, D. Migilinskas, L. Ustinovichius, S. Mikalauskas, The use of a virtual building design and construction model for developing an effective project concept in 5D environment, Autom. Constr. 19 (Mai (3)) (2010) 357–367.
[63] C. Merschbrock, B.E. Munkvold, Effective digital collaboration in the construction industry –A case study of BIM deployment in a hospital construction project, Comput. Ind. 73 (October) (2015) 1–7.
[64] P. Smith, BIM & the 5D project cost manager, Proc. Soc. Behav. Sci. 119 (2014) 475–484.
[65] "Auf dem Weg in die Welt von Handwerk 4.0" – AKTIV-Entscheidungshilfen für den Wandel," 16/3589, Mar. 2016.
[66] S. Groves-Delphos, Cloud Computing, BIM trends in construction industry, The BIM Hub (March) (2014).
[67] M. Webster, ARC Launches SKYSITE, Brings IoT to Construction Industry – World Industrial Reporter, 28-May-2016.
[68] J. McMalcolm, How big data is transforming the construction industry, Construction Global (January) (2015).
[69] R. Burger, How the construction industry is using big data about.com careers, About.Com Careers (August) (2015).
[70] L. Welsh, 2015 Construction Technology Report, JBKnowledge Inc., 2015.
[71] D. Spath, O. Ganschar, S. Gerlach, M. Hämmerle, T. Krause, S. Schlund, Produktionsarbeit der Zukunft –Industrie 4.0, Fraunhofer-Institut für Arbeitswirtschaft und Organisation, Stuttgart, Studie, 2013.
[72] R. Grover, T.M. Froese, Knowledge management in construction using a SocioBIM platform: a case study of AYO smart home project, Procedia Eng. 145 (2016) 1283–1290.
[73] S. Azhar, J.M. Abeln, Investigating social media applications for the construction industry, Procedia Eng. 85 (2014) 42–51.
[74] A. Heathman, Social media and the construction industry Move Commercial, Move Commercial (March) (2015).
[75] IDC, CEMEX Process & IT Transformation: Delivering Value Through an Integrated Business Process Model, (2013) [Online]. Available: http://www.cemex.com/MediaCenter/files/IdcCaseStudyCemexProcessItTransformation.pdf. (accessed: 23.01.16).
[76] A. Davies and D. Sharp, RICS Strategic Facilities Management. Case studies, International Workplace, Cambridge, Report, 2014.
[77] IET, The Institution of Engineering and Technology, Digital Engineering and Project Controls in the Construction Industry, (2012) [Online]. Available: http://www.theiet.org/sectors/built-environment/files/Laing-digital-casestudy.cfm. (accessed: 24.01.16).
[78] Microsoft, Construction Firm Uses Cloud-Based Tools to Advance Mobility and Productivity, (2014) [Online]. Available: https://www.google.de/url?sa=t&rct=j&q=&esrc=s&source=web&cd=10&ved=0ahUKEwiqo9H-1bHKAhXk63IKHR2vDf8QFghuMAk&url=https%3A%2F%2Fcustomers.microsoft.com%2FPages%2FDownload.aspx%3Fid%3D10787&usg=AFQjCNFN7jbY9jj-clqUP7KViRgYbZ5WWA. (accessed: 23.01.16).
[79] K. Chen, DPR Construction, Deloitte University Press, 2013 [Online]. Available: http://dupress.com/articles/dpr-construction/. (accessed: 24..1.16).
[80] KRONOS, Crossland Construction Saves $850, 000 in Labor Costs Using Kronos Automated Workforce Management Solution, (2014) [Online]. Available: http://enewsletters.constructionexec.com/techtrends/files/2015/02/Kronos-Case-Study-Crossland-Construction-Saves-850000-in-labor-costs-with-automated-workforce-management-solution.pdf. (accessed: 23.01.16).
[81] Velocloud, Devcon Provides Reliable Access to Cloud Apps and Improves Remote Collaboration, (2015) [Online]. Available: http://www.velocloud.com/customers/case-study-devcon. (accessed: 23.01.16).

[82] TI Security, Case Study –Russells Construction, 2015.
[83] R.S. Kaplan, D.P. Norton, The Execution Premium: Linking Strategy to Operations for Competitive Advantage, 1st ed., Harvard Business Review Press, Boston, Mass, 2008.
[84] P. R. Allison, How building information modelling is changing the construction industry, ComputerWeekly, March, 2015.
[85] H.L. Guo, H. Li, V. Li, VP-based safety management in large-scale construction projects: a conceptual framework, Autom. Constr. 34 (2013) 16–24.
[86] F. Vahdatikhaki, A. Hammad, Risk-based look-ahead workspace generation for earthwork equipment using near real-time simulation, Autom. Constr. 58 (Oktober) (2015) 207–220.
[87] P. Mullis, Entering the safety zone: how IoT can improve construction sites, HPE Enterprise Forward (January) (2016) [Online]. Available: http://hpe-enterpriseforward.com/entering-safety-zone-iot-can-improve-construction-sites/. (accessed: 28.05.16).
[88] K. Slowey, How BIM is revolutionizing the construction industry, Construction Dive (May) (2015).
[89] J.-S. Chou, K.-C. Yeh, Life cycle carbon dioxide emissions simulation and environmental cost analysis for building construction, J. Clean. Prod. 101 (2015) 137–147.
[90] H. Yuan, J. Wang, A system dynamics model for determining the waste disposal charging fee in construction, Eur. J. Oper. Res. 237 (3) (2014) 988–996.
[91] P. Tang, D. Cass, A. Mukherjee, Investigating the effect of construction management strategies on project greenhouse gas emissions using interactive simulation, J. Clean. Prod. 54 (2013) 78–88.
[92] R. Owen, R. Amor, M. Palmer, J. Dickinson, C.B. Tatum, A.S. Kazi, M. Prins, A. Kiviniemi, B. East, Challenges for integrated design and delivery solutions, Archit. Eng. Des. Manag 6 (4) (2010) 232–240.
[93] K. Hegemann, Are These Technologies the Future of the Construction Industry?, ForConstructionPros.com, 14-May-2015.
[94] Y. Chen, J.M. Kamara, A framework for using mobile computing for information management on construction sites, Autom. Constr. 20 (7) (2011) 776–788.
[95] J. Laitinen, Model Based Construction Process Management, Kungl Tekniska Högskolan Royal Institute of Technology, Stockholm, 1998.
[96] C. Urquhart, H. Lehmann, M.D. Myers, Putting the 'theory' back into grounded theory: guidelines for grounded theory studies in information systems, Inf. Syst. J. 20 (no. 4) (2010) 357–381.

Thuy Duong Oesterreich is a research associate at the chair of Accounting and Information Systems, which is part of the Institute of Information Management and Corporate Governance at the University of Osnabrueck, Department of Economics and Business Administration. She obtained her master degree in Business Administration at the University of Applied Sciences in Osnabrueck in 2008 and is currently carrying on her PhD in Information Systems. Her research interests lie in the field of Industry 4.0 with a special focus on socio-technical and socio-economic aspects in the specific context of the construction domain.

Frank Teuteberg is a full Professor at the University of Osnabrueck in Germany. Since 2007 Frank Teuteberg has been head of the research group in Accounting and Information Systems, which is part of the Institute of Information Management and Corporate Governance at the University of Osnabrueck. Frank Teuteberg is a member of the German Logistics Association. He teaches at Virtual Global University (www.vg-u.de) and is a regular visiting professor at ESCEM (www.escem.fr) in Tours/Poitiers (France). Furthermore, Prof. Teuteberg was the leader of several research projects and subprojects (e.g. Mobile Supply Chain Management 2004–2007 as part of the joint project MIB –"Mobile Internet Business") and he is the founder of the research network ERTEMIS (www.ertemis.eu), which is funded more than 2 million Euros by EFRE and Lower Saxony (project "IT-for-Green"). Since Nov. 2015 he is the leader of a subproject called "Dorfgemeinschaft2.0"on Human-Computer-Interaction/eHealth which is funded more than 5 million Euros by BMBF and project leader of the project eCoInnovate IT which is funded more than 1.77 million Euros by VolkswagenStiftung (www.ecoinnovateit.de). He is author of more than 220 papers in the field of cloud computing, sustainable supply chain management, human computer interaction, and business process management.