Automation in Construction 94 (2018) 22–38

Contents lists available at ScienceDirect

Automation in Construction

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

Construction automation: Research areas, industry concerns and suggestions for advancement

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ARTICLE INFO

Keywords:
Construction automation technologies
Cluster mapping
Text mining

ABSTRACT

Construction automation has shown the potential to increase construction productivity after years of technical development and experimenting in its field. Exactly how, and the possible benefits and challenges of construction automation, though is unclear and missing from current research efforts. In order to better understand the comprehensive potential of construction automation for increasing construction productivity and the associated possible ramifications, an objective and data-driven review of the use of automation technologies in construction was done. The review was accomplished by using text mining methods on publically available written documents, covering a wide range of relevant data including scientific publications and social media. The text mining software VOS Viewer and RapidMiner Studio were used to determine the most promising areas of research through the analysis of scientific publications, and the main areas of concern of industry through the analysis of text on social media, respectively. These research areas and concerns are summarized in this paper, and based on them suggestions for industry are made to help advance the uptake of automation in construction.

1. Introduction

The construction industry is falling behind others in terms of making productivity gains [1, 2]. One of the most promising ways to improve productivity is through the automation of parts of the construction process, which of course, can happen in many different ways, including the increased use of cross-functional teams in construction projects where emphasis is placed on learning and deploying the latest technologies, such as of the use of scrum techniques [3] or the use of robots to replace onsite labors [4, 5]. As many people both in research and in industry are working vigorously in the field of construction automation, a synthesis of their work and suggestions of where future efforts should be focused is of considerable interest to people trying to improve construction productivity.

One of the challenges of providing an overview of construction automation is that different people have different interpretations of what is meant with the words construction automation. For example, most designers consider it as a way to automate the planning and design of projects, but construction contractors consider it as the use of robots for onsite tasks. For example, some specialty construction contracting firms have developed prototypes of single-application robots (e.g., bridge painting robot, concrete blasting robot, rebar placement robot, fireproof coating robot and steel-skeleton welding robot, road maintenance robot) [6, 7]. Given different interpretations, a conventional literature review is difficult to conduct. First, the appropriate articles, or pieces of text, need to be found, and then they can be reviewed.

Finding the appropriate articles can be done using text mining methods for both the analysis of structured text [8, 9] (e.g. journal articles), and the analysis of unstructured text [10, 11], such as social media [12] (e.g., webpages of blogs and online news, podcasts (e.g., Twitter), web communities and blogs (e.g., Reddit Construction Blog), knowledge generating platforms (e.g., The Construction Index website), and web-based news (e.g., Construction News), among others). Text mining methods can be used to scour many different articles to obtain a general overview of the developments related to a specific topic, a scientific domain or a research area including the identification of patterns and relationships between new developments and, the tracking of how areas of strategic importance change over time [13]. Labonnote et al. [14], for example, used citation databases to identify journal publications with information that would be helpful in the investigation of the extent with which additive manufacturing technologies could be successfully applied to large-scale construction projects. Most of the

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https://doi.org/10.1016/j.autcon.2018.05.028
Received 8 December 2017; Received in revised form 19 May 2018; Accepted 28 May 2018
Available online 07 June 2018

text mining analysis included the use of CiteSpace [15] and the Science of Science tool (Sci2) [16]. Khadjeh Nassirtoussi et al., [17], for example, used text mining on the major news webpages (e.g., webpage of Financial Times) to identify texts that would be helpful in the investigation of customer emotional sentiment preserved in the text to gauge the quality of market reception for a product.

The review presented in this paper was done by using VOS Viewer [18] and RapidMiner Studio [19] to identify the collected texts to investigate the developments in construction automation in research through the analysis of scientific publications, using text mining algorithms on Web of Science indexed journals (the journals shown in the Appendix Table 11), and text on social media from the websites (the websites shown in the Appendix Table 12), respectively. Based on the developments mentioned in these texts, suggestions were made as to how researchers and construction companies should focus their efforts to enable the construction industry to obtain maximum benefit from increasingly automating construction projects. The four steps used for both the analysis of the research publications and the social media were 1) determine exact research context, when starting with a general research context, 2) retrieve text, 3) assess data quality, and 4) model and visualize the patterns. With the analysis complete, the suggestions were made taking into consideration how the construction industry is most likely to benefit from increasing automation and how it might be hindered in developing in this direction.

2. Construction automation

Construction automation has many general definitions and different people see it at different levels of generality. For example, very generally a definition of "construction automation" was proposed by Bock [20] as a new set of technologies and processes that will change the whole course and idea of construction in a fundamental way. Jung et al. [21] used a more exact definition, referring to "construction automation" as a machine-centered construction factory technology for applying robotic systems on the construction field. A more limited definition was used by Vähä et al. [22] by describing "construction automation" as the automatic assembly method enabled by computer numerical control and real time sensing technologies. Skibniewski et al. [23, 24] used the term construction automation to principally mean the execution of construction tasks using robots. Their work showed that the automation of construction tasks requires substantial adjustments to the construction schedule and shifting of project recourses. Since the concept of Industry 4.0 has been introduced as a popular term for digitalization and automation of the manufacturing environment, the definition of construction automation has been extended to include information modelling and digitalization [25]. Some researchers argue that "construction automation" is the integration of computer-aided design and robot-based onsite technologies for simplification of overall activities [26]. A few of them, such as Willmann et al. [27], now use the term "digital fabrication" to as a synonym for "construction automation", particularly when referring to customized building construction. The definition used in the work presented in this paper in the search for new developments in the field of "construction automation" was the use of technologies younger than 20 years in the design and construction processes with the goal of improving construction productivity.

3. Text mining processes

Text mining processes for structured and unstructured text are different. Structured texts, such as journal publications have a clear abstract, introduction and conclusions, and contain lists of keywords, whereas unstructured texts, such as though found on social media do not. Although numerous software packages for text mining exist, and they all use the same analyzing process, some are more useful for analyzing structured texts and others for unstructured texts. In this work, VOS Viewer, was used for the structured text analysis and RapidMiner Studio was used for the analysis of unstructured texts. VOS Viewer is a computer software primarily used for creating, visualizing and exploring bibliometric maps of scientific publications. It is able to convert the publication information into a text corpus for statistical analysis of words. It can be used to analyze the citation relations between publications, collaboration relations between researchers and co-occurrence relations between scientific terms (i.e., words). The text mining process in VOS Viewer for the analysis of co-occurrence relations between scientific terms consists of using a word similarity function to output a graph with clusters of these words. RapidMiner Studio is computer software that allows to transform text into a format useable for operator processing, such as finding the words that appear together in at least a threshold ratio of occurrences [28]. The text mining process in RapidMiner Studio is usually customized using different operators, wherein the most basic operators include "process documents from files", "convert numerical vectors into binomials", "FP-growth" and "create association rules" [29].

Both of VOS Viewer and RapidMiner Studio analyze documents or text files with the same text mining algorithms (e.g., similarity functions) in order to construct and visualize the important words. They are equipped with similar text mining functions and steps, such as calculating the occurrence of a word or a word stem as the first step. Although the final outputs of the two software display in different forms, they both show the important words that are relevant to construction automation as well as their relatedness. The analytic results from VOS Viewer and RapidMiner can be compared.

Either for VOS Viewer or in RapidMiner Studio, the text mining processes consists of four steps (see Fig. 1), with detailed sub processes when using each of the two software to model and visualize patterns. The basic assumptions made in the analyses were: 1) The publications cited from the Web of Science database adequately indicate the developments in research, 2) The most popular and influential websites (i.e., top 50 websites determined by Feedspot [30]) used indicate the developments in practice, and 3) The basic sense of the term "construction automation", has not significantly changed over within the last 20 years (Jan 1997 to May 2017).

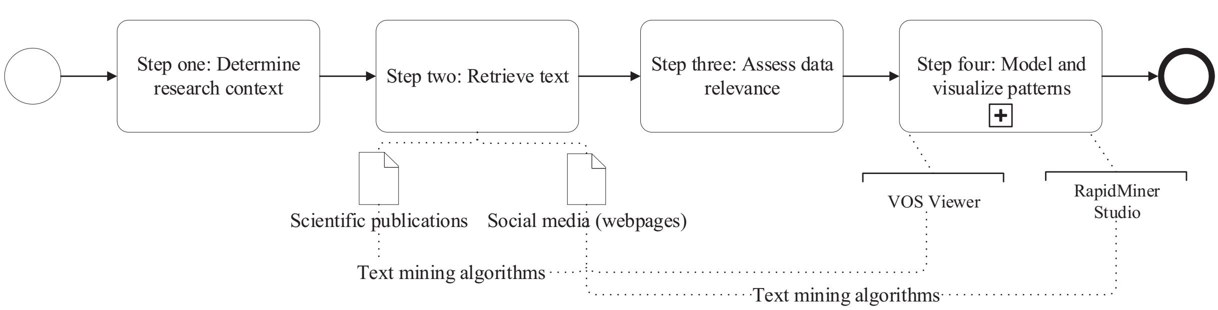

Fig. 1. Text mining process.

3.1. Step one: Determine research context

In this step the research context used to search the texts was determined. Determining the research context clearly is the premise to obtain relevant information regarding a researched topic (e.g., construction automation). A clear research context is required to distinguish relevant texts from non-relevant ones. For example, an article on automation technologies 50 years ago (e.g., a crane) are not relevant if the research context is the state-of-the-art in automation today.

The research context was the search for new developments in the field of "construction automation" defined as the use of technologies younger than 20 years in the design and construction processes with the goal of improving construction productivity, in the construction of residential and industrial buildings, and public infrastructure. Construction automation was assumed to be used in both design (e.g., the use of Computer Aided Design), construction (e.g. to control the use of machines onsite) and management (e.g., the use of Building Information Models). As an additional clarification of research context, it was assumed that construction automation is being used to:

1) Decrease dependency on manual labor, which would decrease the number of problems related to quality, would alleviate the monotony associated with doing repetitive work, and reduce costs by reducing the need for manual labor.
2) Increase productivity, as algorithmic computing and machines can work faster than manual labor.
3) Increase safety and quality, as manual labor can be removed from all dangerous situations.
4) Increase control over the design and construction processes, as machines can be monitored continuously and in very detailed ways without affecting their performance, where as humans cannot.

As it is difficult to distinguish a conventional construction automation technology (e.g., a construction worker operating a crane) from the state-of-the-art construction automation technology (e.g., completely unmanned robot fabricator), no distinction between the two were made. Instead, it was assumed that by limiting the analyses of the structured text analysis to publications in the last 20 years, and only considering current web sites for the unstructured text analysis, that only state-of-the-art construction automation technology would be captured.

3.2. Step two: Retrieve text

In this step, the structured texts were retrieved from the scientific publication database of Web of Science and the unstructured texts were retrieved from the 35 relevant publically available construction blogs of the top 50 determined by Feedspot using Web Scraper [31] (see column "Applicable for data retrieval" in Appendix). Web Scraper, a web harvesting or web data extraction tool, is used for automatically fetching and extracting texts from websites. Web pages (shown by the web links) are built using text-based mark-up languages (e.g., HTML and XHTML), and frequently contain useful data in text form. Web Scraper is able to parse these web links into text formats. The selection of social media data webpages relies on the web harvesting results.

To identify relevant texts, search rules were used, which are simply the linked Boolean operators (e.g., construction robot AND building construction NOT manufacturing as an inclusion-exclusion mixture criteria for searching). The search rules for publications used are given in Table 1. They were used to find publications on how construction automation technologies, such as a construction robot, are used in a particular context, such as building construction. The search excludes the topics on unrelated subjects, such as "manufacturing" that was focusing on automation in manufacturing industry, "hardware" and "software" that were associated with specific advancements in computer configurations and computer systems.

Table 1
The search rules of publications in Web of Science.

How	AND	What	NOT	To exclude
Construction robot		Building construction		Manufacturing
Building information model		Construction cost		Hardware
Industrial 4.0		Construction schedule		Software
Digital fabrication		Construction performance		
3D printing		Construction safety		
Cloud computing		Construction survey		
(Virtual, augmented) reality		Lean construction		
Drone				

The results returned 5087 publications. Of these publications additional filtering was used to eliminate irrelevant publications, e.g. by removing publications in the field of nuclear science which were concentrating on automating nuclear experiments rather than the automation of building nuclear power plants. The data of 741 remaining publications were stored in text files, with their data structured in titles, keywords, abstracts, journal source, and cited references. The distribution of 741 scientific publications from 1997 to 2017 is shown in Fig. 2. It can be seen that the number of relevant scientific publications has drastically increased over time. It is also noted that the number of scientific publications in 2017 is not complete as publications were retrieved up to May 2017. Top 10 journals ranked according to percentage of publications retrieved is shown in Table 2, indicating the percentage of publications that come from the same source of journal. Most of the extracted scientific publications are from the Journal of Automation in Construction.

The search rules for social media publications were not as easy to construct as for scientific publications, since webpages have limited capability of applying Boolean operators when compared to Web of Science. In their place, the search word, "construction automation" was entered on each webpages to further filter all the web links containing "construction automation". Then these web links, built upon text-based mark-up languages, were parsed by Web Scraper in order to extract all the data of blogs, news, etc. All the data extracted from the 35 websites was stored in text files for further analysis. The text data included information of construction automation case studies as well as opinions and trends on industrial applications.

3.3. Step three: Assess text relevance

To ensure that the results of text mining were as good as possible, in addition to conforming to the research context and search rules, the relevance of each text was manually assessed, with respect to the

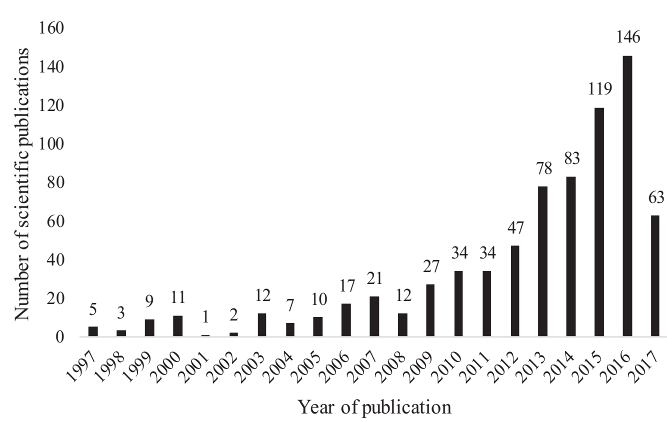

Fig. 2. Distribution of 741 scientific publications from 1997 to 2017.

Table 2
Top 10 journals ranked according to percentage of publications retrieved.

Name of journals	Publications retrieved (%)
Automation in construction	28.5
Journal of construction engineering and management-ASCE	10.5
Journal of management in engineering	3.5
Journal of information technology in construction	3.4
Journal of civil engineering and management	3.2
Building and environment	2.6
KSCE journal of civil engineering	2.2
Engineering structures	1.9
Canadian journal of civil engineering	1.6

following factors, as suggested by Lee [32]:

1) The state of completeness, validity, consistency, timeliness and accuracy that makes data appropriate for a specific use (i.e., data is accessible for processing in VOS Viewer and RapidMiner Studio).
2) Degree of excellence exhibited by the data in relation to the portrayal of the actual scenario (i.e., data is not skewed and is able to reflect the actual trends in construction automation).
3) The totality of features and characteristics of data that bears on its ability to satisfy a given purpose (i.e., all the retrieved data is robustly related to the research context and the keyword "construction automation").

If the answer was yes to all of these then the text was considered relevant. If one was considered to be no then the text was considered not relevant and removed from the analyses. In this work, all 741 scientific publications and 35 selected websites were deemed relevant after manually screening the retrieved texts. For scientific publications, the "titles" and "abstracts" attributes were read and checked manually. Without "title" or "abstract" attributes that were split by delimiters, the plain texts retrieved from webpages were mechanically checked line by line. All the retrieved texts were relevant because

1) their completeness, validity, consistency, timeliness and accuracy were guaranteed by the sufficient amount of extracted texts over a long period of time; scientific publications over years from 1997 to 2017 and social media data without specifying any time limit,
2) the degree of excellence exhibited by the data in relation to the portrayal of the actual scenario was ensured through obtaining the articles from top peer reviewed journals and top ranked websites,
3) the totality of features and characteristics of data that bears on its ability to satisfy a given purpose was ensured through the manually checking the details of texts.

3.4. Step four: Model and visualize patterns

The structured text analysis was done using VOS Viewer. The main tasks of the text mining process using VOS Viewer are shown in Fig. 3. The first step was to extract titles and abstracts generated from the scientific publications. The number of occurrences of each word was then calculated and using a threshold of 10 occurrences, as suggested by Van Eck [33], the relevancy of the word was decided, i.e. if a word was seen ten or more times it was considered relevant and otherwise not. Words not directly related to the automation of construction, such as "article", "paper", were also removed. The similarity of two selected words was calculated using the similarity function shown in Eq. (1) which has been used extensively in clustering algorithms [34]. For example, if the total number of occurrences of "automation" is 31, the total number of occurrence of "accuracy" is 40, and the number of co-occurrences of "automation" and "accuracy" is 25. Then the similarity between "automation" and "accuracy" is $25 / (31 * 40) = 0.02$. Similar words were then clustered together, given a title and classified as main research areas. Their similarity could also be visualized by the distance between two words in the output figure in VOS Viewer. The shorter distance between the two words, the higher degree of similarity (i.e., higher relevance).

$$S_{ij} = \frac{c_{ij}}{w_i w_j} \tag{1}$$

where, S_{ij} = similarity between word i and word j. c_{ij} = number of co-occurrence of word i and word j. w_i, w_j = total number of occurrence of word i, word j.

The unstructured text analysis was done using RapidMiner. The main tasks of the text mining process using RapidMiner Studio are shown in Fig. 4.

In step 1, the texts were submitted to the software through the use of the "process documents from files" operator, which transforms the text into a word stem list represented by numerical vectors. This was done using four sub steps: tokenizing, transforming cases, filtering stop-words, and stemming words. The text to be analyzed can be viewed as a vector representation of tokens. Each entry in that vector is the presence or absence of words, which will further be converted to binary numbers corresponding to a word or word stem of that text. Tokenizing was used to break a stream of text (i.e., paragraphs) up into words and symbols, which are called tokens. These tokens were then converted to one case (either lower case or upper case). Prepositions, articles, and pronouns, were removed from the analysis through the sub step: filtering stop-words. Word stems were then created from the remaining words, e.g. the word stem "manag" is stemmed from the word "manage".

In step 2, the numerical vectors (i.e., word stem lists) were converted into binomials. Binominals can have only two possible values; True or False. The original numerical vector, after conversion, would have all the entries with "True" or "False", depending on whether the words were encountered in the text. In other words, the values "True" or "False" indicate whether the words from text mining corpus library were contained in the text. It is also noted that still two parameters have to be specified: the min and max values for determining "True" and "False". For example, if min value is set as 0.0 and maximum value is set as 0.1, the number inside the numerical vector that falls in the range from 0.0 to 0.1 is mapped to "False" and the others are mapped to "True". Under this condition, the word stem "manag" with an entry value of "1" in the original numerical vector, because of the value being between 0.0 and 0.1, would be mapped to "False".

In step 3, the operator "FP (frequent patterns)-growth" was used to process the binomials that were generated from step 2. FP-growth is an operator that generates frequent word stems, calculates all the frequent word stem pairs that appear together, and produces a FP-tree data structure. The FP-growth final output, the FP-tree data structure, was specifically produced for "association rules" [35]. The FP-tree data structure is a compressed form of the binomials, consisted of tree paths and nodes that represent the frequency and interactions of word stems.

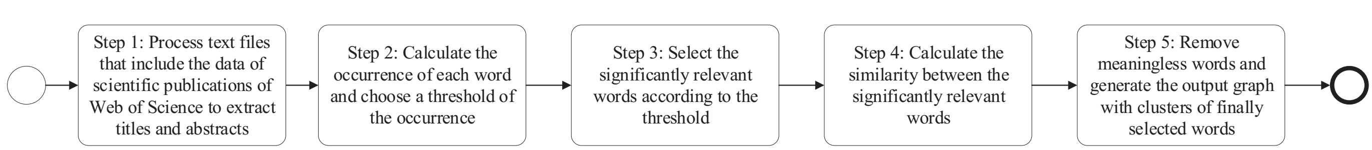

Fig. 3. Main tasks of the text mining process using VOS Viewer.

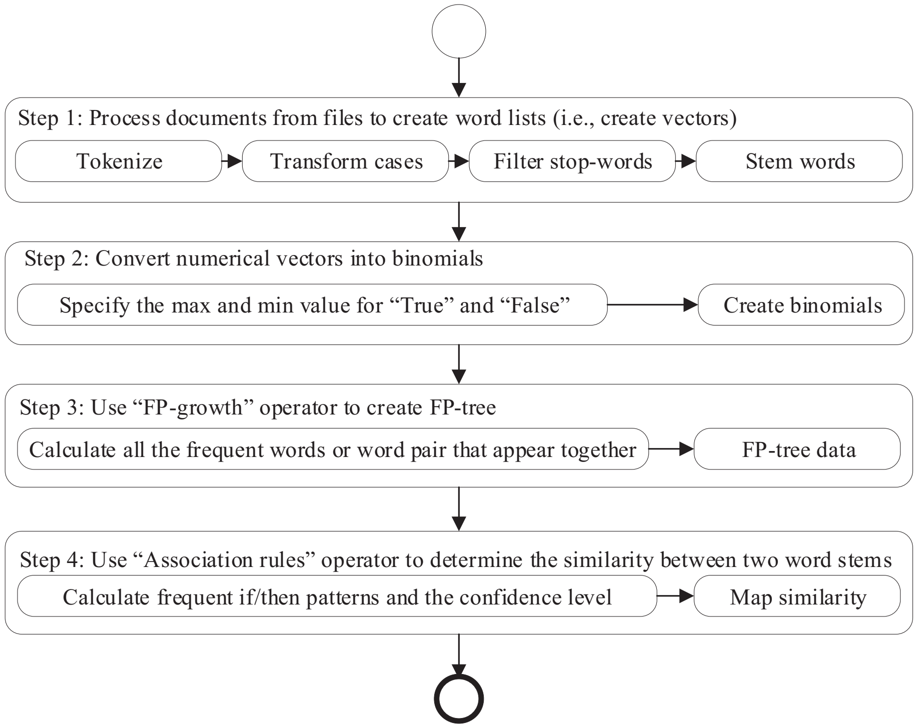

Fig. 4. Main tasks of the text mining process using RapidMiner Studio.

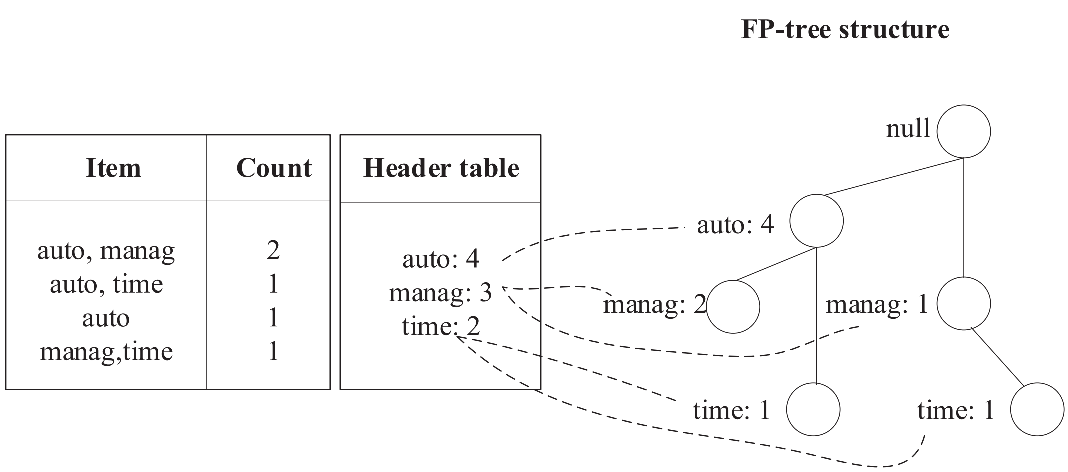

Fig. 5. A simple example of FP-tree structure.

The generation of FP-tree was done in an FP-growth algorithm that can output the “support” values of a group of words occurring frequently in a text. Support is an indication of how frequently a given word appears in the text, corresponding to the value of each node in the FP-tree data structure. In order to implement FP-algorithm, the occurrence of each word stem was counted and stored in a header table first, and then an initial FP-tree structure was created through inserting instances from the header table. Instances were sorted by descending order of their frequency in the dataset, so that the FP-tree structure can be processed iteratively and quickly. A simple example of FP-tree structure is given in Fig. 5, which starts computing with a root node labeled as a “null node”. As an example from Table 7, the word stem “manag” was calculated as 95.528 in the FP-tree data structure, which indicated its frequency in the text.

In step 4, the operator “association rules” was used to calculate the FP-tree data and determine the similarity between word stems. The operator works by analyzing data for frequent if/then patterns and the confidence level to identify the most important relationships. The frequent “if-then” patterns for a stream of text (or converted to binomials) were produced using the FP-growth operator, which generate the FP-tree data. An example of an association rule would be “If a customer buys eggs, he is 80% likely to also purchase milk.” Then among the FP-tree data, a premise word j (i.e., the antecedent “if” item) and a conclusion word i (i.e., the consequent “then” item), are linked by support, which is the number of co-occurrences of the word i and word j. The confidence level is then calculated, which indicates the number of times the “if” (a premise word) -“then” (a conclusion word) statements have been found to be true. The confidence level is calculated by dividing the numbers of co-occurrences of word i and word j by the total number of occurrences of word i (see Eq. (2)). Creating association rules takes these frequent sets of word-pairs and generates their associations. For example, if the total number of occurrence of “auto” is 1000, and the number of co-occurrences of “auto” and “market” is 1000. Then the confidence level that “auto” implies “market” is 1, meaning that if auto appears in a paragraph, there is 100% likelihood that market also appears in that paragraph.

$$ConL_{ij} = \frac{Sup_{ij}}{Sup_i} \tag{2}$$

where, $ConL_{ij}$ = the confidence level that word i implies word j. Sup_{ij} = the number of co-occurrence of word i and word j. Sup_i = the total number of occurrence of word i.

4. Results

4.1. Main research areas

The structured texts containing information of scientific publications were analyzed in VOS Viewer following the steps in Fig. 3. Similar words were clustered together (as represented by the different colors), classified as main research areas, and given a specific name. Within a given cluster, words were ranked based on the number of publications in which they were found. This was reflected by the size of the circle for each word. The distance among the circles provides an indication of relatedness, so that the closer the circles the higher the relatedness of the words. The colors were assigned automatically and range from blue to green to red. In Fig. 6, the green, blue and red circles indicate words associated with clusters 1, 2 and 3, respectively. The degrees of relatedness between words are indicated by the curved lines.

The words associated with each other and their relationships are also shown in Fig. 6. The number of word occurrences in each cluster are given in Table 3.

When observing Fig. 6, it is important to realize here that the words shown are only of importance within the research context and with respect to the associated research area. For example, "structure" in the blue cluster (i.e., Construction Managerial Objectives) is associated with the physical building structure and structural analysis, rather than the company's organizational structure, which is associated with building function, building quantity takeoffs and so on. Within and among the clusters, the distance between two circles offers an indication of the relatedness of them. For example, the distance between "safety" and "construction site" is short, meaning that the two words often appear together and are highly relevant. Interpretation of the results found by the VOS Viewer is given in Table 4, Table 5 and Table 6. Specific publications are cited in the interpretation to point the reader to sources of more information. When putting the results (e.g., relevance or words) in context, which is provided in the selected scientific publications, the results become more meaningful. The main benefits of implementation of construction automation can be summarized as: 1) improving the efficiency of work processes, 2) enhancing the communication and collaboration between stakeholders, and 3) a potential to increase market share.

4.2. Main industry concerns

Unlike VOS Viewer, the RapidMiner does not produce the clustering graphs. After implementing the "FP-growth" and the "association rule" operators shown in Fig. 4, the most frequent word stems and most associated word-stem pairs were compiled into a table format. Each word stem reflects a specific concern or theme from the texts that it belongs to. If a word stem identified with a given concern had a high frequency online with its highly associated word stem, the more important the concern was assumed to be. The most frequent word stems are summarized in Table 7 and the top ten most associated word-stem pairs produced from the association rules are shown in Table 8. When going over Table 7 and Table 8, it is important to realize that the meaning of

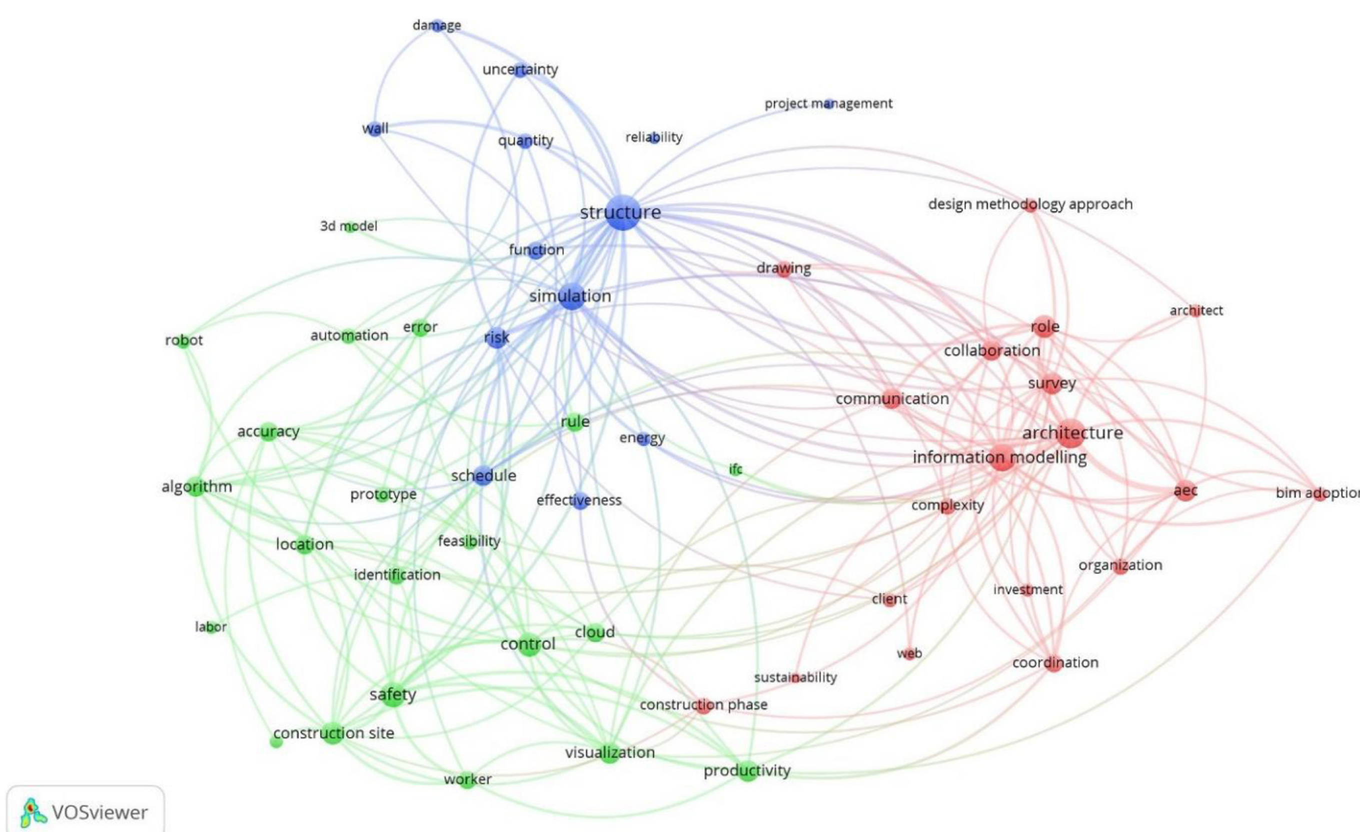

Fig. 6. The words, and their relationships with each other, used to identify the three main research areas, (1) Construction Robots and Automation Systems – green (the left bottom part), (2) Construction Managerial Objectives – blue (the left up part), and (3) Building Information Modelling Based Collaborations – red (the right part). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
Number of word occurrences in each cluster.

Green cluster (area 1): Construction Robots and Automation Systems		Blue cluster (area 2): Construction Managerial Objectives		Red cluster (area 3): Building Information Modelling Based Collaborations	
Word	Word occurrence	Word	Word occurrence	Word	Word occurrence
Control	55	Structure	180	Information modelling	86
Safety	51	Simulation	76	Architecture	81
Construction site	47	Risk	44	Survey	62
Algorithm	44	Schedule	43	Role	55
Productivity	43	Function	40	Communication	40
Visualization	41	Wall	33	Collaboration	40
Accuracy	40	Effectiveness	31	aec	40
Location	38	Energy	28	Organization	37
Rule	34	Quantity	26	Coordination	33
Identification	33	Uncertainty	25	Drawing	31
Error	31	Damage	25	Complexity	28
Automation	31	Project management	23	Construction phase	26
Cloud	29	Reliability	18	Investment	24
Prototype	27			Client	24
Robot	26			Web	23
Feasibility	26			Architect	23
Worker	25			Design methodology approach	22
3d Model	20			Bim adoption	22
ifc	18			Sustainability	18
Labor	16				

Table 4
Interpretation of the VOS viewer results: Construction Robots and Automation Systems - green cluster.

No.	Result	Interpretation – this reflects the fact that…	Benefits or challenges
1	"Control", "safety", "construction site" and "algorithm" are highly relevant	A number of scientific publications on construction robots and systems focus on optimizing the control of machines [36] and improving safety of operators [37], particularly on construction site [38].	Benefits: improving the efficiency of work processes
2	Robots and other automation technologies, represented by words such as "visualization", "identification", "location accuracy", are grouped with "construction site"	There is an increasing use of technology during the construction phase, e.g., radio frequency identification technology (RFID) [39] has been integrated with material identification and locating processes to enhance the just in time delivery of construction materials [40]. Robots have recently been designed for tasks such as painting, and jointing in buildings have higher efficiency with respect to pay load, reach, number of degrees of freedom, etc. [41, 42]. Robots have been developed to perform autonomous construction tasks onsite, with customized abilities [43] to manipulate construction materials and equipment [44, 45]. Robots known for "swarm behavior", have recently become attractive for additive construction, since unlike large-scale bricklaying robots, they are smaller so that they can find their own way to specified construction location without human intervention [46].	Benefits: improving the efficiency of work processes
3	"3D printing" and "digital fabrication" do not appear as relevant words	Even though they are considered as primary components to drive the use of construction robots [47, 48], 3D printing and digital fabrication are not yet dominating the current construction trend or being mature for extensive applications, and therefore cannot be expected to show up in such an analysis.	Challenges: a lack of maturity of use of information
4	There are only a few links between the green and red clusters	There is a lack of research on how to combine computer aided design with onsite robotic and automation systems.	Challenges: a lack of maturity of use of information
5	There are no strong relationships existing between BIM technology and task-oriented robots	There is a lack of research linking automated design and construction integration	Challenges: a lack of maturity of use of information

each word stem should be interpreted with respect to the theme of the text to which it belongs. An interpretation of the most frequent word stem and most associated word-stem pairs is presented in Table 9. The interpretation of the results includes reflection on whether this aspect of construction automation brings benefits or challenges.

The most frequent word stems found in social media texts are "construct", "market", "product", "manage", "use", "cost", "time" and "company" (Table 7). The results confirm that industry cares more about the benefits and challenges that will influence final construction products. It is discernible that the most frequent word stems also appear in the most associated word-stem pairs, for example, the word-stem pair "increas - product, design, industri, manag" includes each word stem as the most frequent.

According to Table 8, a confidence level of one indicates that there is high probability of the "if" (a premise word) - "then" (a conclusion word) statements found to be true. These ten word-stem pairs, such as "technolog-market, system" and "manag-design, industi", indicate an active interaction between company development, market and technologies. Unlike academic research field, social opinions tend to address problems encountered in practice. It is noted that the top ten word-stem pairs do not contain any specified technology used, such as a specific type of design software or a specific robot. This reflects the company development instead of particular features of a technology. According to the most associated word-stem pair "increas-product,

Table 5
Interpretation of the VOS viewer results: Construction Managerial Objectives - blue cluster.

No.	Result	Interpretation – this reflects the fact that…	Benefits or challenges
1	The most relevant words are “simulation”, “risk”, “schedule” and “function”	The primary managerial objectives in running construction projects are the focus of simulation [49] and optimization in order to reduce time and risk.	Benefits: improving the efficiency of work processes
2	The blue and red clusters, and the blue and green clusters are closely linked	There is work being focused on improving the management of construction projects by through the use of construction automation technologies and stakeholder collaborations.	Benefits: enhancing the communication and collaboration between stakeholders
3	The word “construction schedule”, appears the most frequently in relation to construction automation	Out of the many possible management objectives, there is perhaps the most work focused on improving the schedule.	Benefits: improving the efficiency of work processes
4	There are limited links among the words within the blue cluster; but many between the blue and the red and green clusters.	Attempts to achieve management objectives are often done through simulations using the techniques associated with other clusters, e.g. automation and building information modelling. A distinct emphasis on improving the schedule and reduce project time using automatic approach, e.g., strong relatedness between BIM and schedule [50]. Improve scheduling using 4D modelling to avoid modelling errors and construction activity conflicts [51, 52].	Benefits: enhancing the communication and collaboration between stakeholders with the help of model visualization and sufficient information exchange Challenges: a lack of maturity of use of information
5	The management objectives are linked with the green and blue cluster	Recent research has been focused on developing algorithms or prototyping of automation technologies to help achieving management objectives and improve the efficiency of project management.	Benefits: improving the efficiency of work processes with respect to different objectives
6	The words “simulation” and “project management” are strongly associated with BIM-based decision making process and information communication technologies from the red cluster.	BIM provides a collaborative decision-making platforms to facilitate information sharing [53, 54] for model simulation (e.g., 4D simulation for visualization of a building process) and project management (e.g., scheduling control), and that web technologies and artificial intelligence enables access to a vast amount of information from multiple sources easier in construction industry [55]. This can be seen in the work of a number of researchers who have proposed knowledge based decision making models [56, 57] to support time-cost-quality trade-off analysis [58].	Benefits: enhancing the communication and collaboration between stakeholders

Table 6
Interpretation of the VOS viewer results: Building Information Modelling Based Collaborations – red cluster.

No.	Result	Interpretation – this reflects the fact that…	Benefits or challenges
1	There is a high occurrence and co-occurrence of the words “information modelling”, “communica-tion”, “coordination”, “coll-aboration” and “complexity”	There are large advantages to be obtained by using BIM to enable collaborative working environments, which help to reduce miscommunication and errors among construction players [59, 60]. To help the automation of scheduling and project planning process [61, 62].	Benefits: enhancing the communication and collaboration between stakeholders
2	The “information modelling” and “complexity” circles are large.	BIM facilitates solving project complexity problems, either with respect to the building design or the collaboration of participants in all project phases [63]. This also coincides with the increasing number of contractors and owners who are experiencing changing roles when involved in BIM-based projects [64], as the traditional hierarchical organizational framework is gradually taken over by a new framework with more effective communication, coordination and collaboration among organizational members, due to the computer-supported benefits of BIM.	Benefits: enhancing the communication and collaboration between stakeholders
3	“ifc” or “Industry Foundation Class” is a connecting word between the green and red clusters	Interoperability of information is a significant technological problem of using BIM [65]. A few researchers have developed a full-digital design-to-production process, which enables the use of BIM model directly for steel column detailing and robotic fabrication [66, 67]. Problems appear when responsibility for an information model is transferred from designers to contractors [68].	Challenges: a lack of maturity of use of information
4	There is a weak connection between the green and red clusters	There is a lack of information exchange and integration between BIM enabled design and robot enabled automatic fabrication, and therefore a lack of research focused on improving the design-to-production concept through a tight collaboration and interoperability between upstream design automation and downstream onsite operational automation.	Challenges: a lack of maturity of use of information

design, industri, manag”, it is recognized that companies focus on how to increase productivity by innovating product, design processes and management processes. This finding is consistent with the area 1 from the analysis of the scientific publications. In addition, the frequent association between “help-busi, use” and “time-technolog” indicates that the use of construction automation technologies will save time and smooth business operations.

In order to clarify the industry concerns, those frequent word stems and word-stem pairs should be interpreted in the specific context or the extracted texts they belong to. By probing the detailed texts on line,

Table 7
Most frequent word stems.

Cluster	No.	Word stem	Support (i.e., an indicator of occurrence)
Cluster of the most frequent word stems	1	Construct	177.694
	2	Product	143.278
	3	Market	141.789
	4	Manag	95.528
	5	Use	94.111
	6	Cost	91.889
	7	Time	88.361
	8	Company	87.972
	9	Technolog	82.028
	10	System	76.389
	11	Work	75.361
	12	Industri	75.222
	13	Design	51.306
	14	Increas	44.028
	15	Busi	38.667
	16	Help	36.222
	17	Auto	2.806

Table 8
Top ten most associated word-stem pairs produced from the association rules.

No.	Premise word	Conclusion word	Confidence level
1	Increas	Product, design, industri, manag	1
2	Manag	Design, industri	1
3	Technolog, auto	Market, system	1
4	Construct	Technolog, system, cost	1
5	Work	Product, cost	1
6	Help	Use, busi	1
7	Product, combin	Research	1
8	Clear, approach	Govern	1
9	Earli	Resource	1
10	Earli, complex	Transform	1

there exists manifold potentials and unsolved problems related to adoption of construction automation technologies. Table 9 shows the contextual interpretations of the most frequent word stem and most associated word-stem pairs, which implicate the facts about benefits or challenges of construction automation. The construction industry consists of plenty of small and medium size companies with limited capabilities for investment in automation technologies. Some of them are facing increasing challenges through globally economic competition, in turn resulting in limited investment on advanced technologies. A number of websites point out the difficulty of increasing market share in construction projects using automation technologies. It is also discernible that potential risks exist when companies make investment decisions on how and to what level to implement construction automation technologies. Although "risk" is not showing up as one of the most frequent word stem in the results, it is an important concept reflected from contextual information. By relating "risk" to context in the most of webpages shown in Table 9, it is easy to conclude that the construction industry, no matter what size of a company or what level of technological maturity, mainly perceives risk as financial aspects. This also correlates to that high occurrence of "cost" in extracted social media texts.

Based on these contextual interpretations from Table 9, the challenges are summarized mainly as: 1) a lack of maturity of use of information, 2) a lack of company investment, and 3) a lack of economic competition. The benefits seen from contextual interpretation are: 1) a potential to increase market share, 2) improving the efficiency of working processes with respect to different objectives, 3) enhancing the communication and collaboration between stakeholders. Therefore, the next step for the industry is to concern about how to overcome challenges of using automation in construction, and how to estimate the benefits of using automation in construction.

4.3. Summary

As can be seen from the review, researchers are principally focused on pushing the forefronts of science to enable the automation of construction and industry is concerned with overcoming the challenges of implementation and ensuring that implementation is beneficial.

Researchers see that the construction automation system as a whole [79] can be improved by implementing technologies to enable automation. Construction automation enhances collaboration between different stakeholders, shortens the length of time required to complete construction tasks onsite, and hence helps to improve construction efficiency. This can be seen through their focus on the potential of building information modelling and onsite automation systems as two of the main research areas. Of the many ideas researched it seems the greatest potential for innovation will come from the creation of a continuous process that leverages the benefits from integration of design information and construction information, which would allow more efficient information exchange, through helping to ensure information integrity and comprehensiveness, leading to less iterative work between designer and constructor. The clustering also shows that the most significant division of the construction process is in the "separation" of the design and construction phase. With increased implementation of technologies to enable automation, the number of ambiguities in downstream phases of construction will be minimized and less amount of material will be wasted due to the availability of more accurate information. Additionally researchers see that a significant barrier to the use of building information in integrated construction processes is the lack of standardized data schema and a lack of protocol to delimitate the responsibility for information usage.

The main industry concerns are overcoming challenges of using automation in construction, and correctly estimating the benefits of using automation in construction. The challenges include those for single companies, such as overcoming financial difficulties due to the high implementation costs, and overcoming technological barriers such as providing adequate information security and overcoming information exchange problems, and those for the entire industry, such as ensuring that multiple partners in the construction process can work together seamlessly and encouraging the development and use of appropriate tools. It seems that it will be the push to gain market share or maintain competiveness that will be the drivers that push industry to automate. Additionally industry appears to be concerned about having no standardized practices for the estimation of costs and benefits of increasingly automating their construction processes, which casts doubt on any of such studies done, and makes it difficult for decision makers to build strong arguments for change. Industry is also concerned with information security. With the increasing dependency on information available to many partners, there will be increased problems, such as cyber-attacks on web based or BIM-based collaborative platforms, blame when information gets changed by people who are perhaps not aware of the downstream consequences, and are not responsible for them.

5. Suggestions

In order for the industry to overcome the identified challenges and realize the benefits, suggestions, and related justifications for their implementation, are provided for advancing the use of construction automation. Table 10.

6. Conclusions

Construction automation has the potential to increase construction productivity. Exactly how, and the possible benefits and challenges of construction automation, are not clear for everyone. In order to increase this understanding and to help focus industry efforts, and research efforts to help industry, a data driven review through text

Table 9
Interpretation of the most frequent word stem and most associated word-stem pairs.

No.	Word stem or word-stem pair	Contextual information from original social media in examples	Interpretation – this reflects the fact that…	Benefits or challenges
1	Construct - technolog, system, cost	"When it comes to the precise means of incorporating the Internet of Things into construction, …and smart technologies can enhance the operation of built assets and infrastructure… necessarily involve dramatic cost growth…" [69]	Companies put emphasis on overcoming challenges of limited capabilities for investment in automation technologies.	Challenges: a lack of company investment
2	Technolog-market, system	"Every construction company owner faces pressure to control costs and operate at lower profit margins…, determine the types of technologies that will bring the biggest benefit to your organization's bottom line…, stay ahead of their competitors for projects both now and in the future…" [70]	Companies are facing increasing challenges through economic competition when incorporating advanced technologies.	Challenges: a lack of economic competition
3	Increas - product, design, industri, manag	"The Global Construction Robots Market 2016–2020 report, …, but the market will exhibit a promising growth rate over the next four years… that an increase in the construction of mega structures and high-quality infrastructure will necessitate the use of construction robots …" [71]	More companies are applying various automation technologies in construction projects which will lead to an increasing market share.	Benefits: a potential to increase market share
4	Earli, complex - transform	"Since it is well known that early digital adopters will gain an immense competitive advantage…, complex information is immediately shared, … single source of truth to continue to handover to client and beyond…,transformational re-organization to enhance efficiencies…" [72]	Most of construction projects are vulnerable to information attacks as well as failure of information sharing across stakeholders due to the technical difficulties in the early transformation phase.	Challenges: a lack of economic competition
5	Construct - technolog, system, cost	"Bentley Systems demonstrated that the construction projects in the virtual reality technology required on building sites involve a capital cost which must be clearly assessed to reduce risks of implementing construction automation technologies" [73]	Companies still take the risk of balancing cost-benefit when implementing construction technologies in practice.	Challenges: a lack of maturity of use of information
6	Manag - design, industi	"The virtualization of construction is becoming increasingly common…, should make construction managers' jobs easier…, VDC bridges the gap between design data and construction execution…, benefits on supply chain integration and industry leading margins" [74]	Companies are able to benefit from better project management process with the help of integrating information from design and construction.	Benefits: improving the efficiency of working processes with respect to different objectives
7	Earli - resource	"The in-house parametric design software provides comprehensive details at a very early stages…, BIM models are resource intensive…, trade-off between resource required and changeability…" [75]	Companies can gain benefits through parametric design models with less change orders and more communication on sharing recourses.	Benefits: enhancing the communication and collaboration between stakeholders
8	Product, combin-research	"Smaller construction enterprises providing integrated design and manufacturing capabilities are turning to related technological products. It is these technologies that will enable new construction startups to build powerful digital enterprise platforms that combine with an ecosystem of business enabling technologies to challenge their traditional construction counterparts…, a serious investment is needed across construction's academic and training institutions to enable a world class hub for modern construction education and research." [76]	Companies are encouraged to invest in collaboration with construction academic and training institutions on construction automation technologies in order to develop business competitiveness.	Challenges: a lack of economic competition
9	Time - technolog	"Fischer Homes shows that drone survey work offers time and money savings…, considering the worth of drone technology…, track a site's progress with a degree of accuracy previously unknown in the industry…" [77]	Companies are able to enjoy time saving when leveraging the functionalities of various automation technologies.	Benefits: improving the efficiency of work processes with respect to different objectives
10	Help - busi, use	"It would also help offset the impact of a declining share of the working-age population in many countries…, the automation of activities can enable businesses to improve performance by reducing errors and improving quality and speed, and in some cases…" [78]	Companies will increase profitability and productivity by implementing automation to enable an optimized business process.	Benefits: improving the efficiency of work processes with respect to different objectives

Table 10
Suggestions and justifications for advancing the use of construction automation.

No.	Suggestions	Justifications
1	Reengineer business structures and processes	In order to accelerate the use of construction automation to benefit from enhancements in the communication and collaboration between stakeholders and improvements in work efficiency, all participants in the construction process should reengineer their business structures and processes. If structures and processes are adapted ahead of time, stakeholders will be well positioned to implement new technologies and benefit from new partnerships. Close collaborations with researchers can help to ensure that industry is well aware of the emerging technologies.
2	Increase the scale of adoption	The benefits of automating construction greatly increase the more stakeholders are involved, i.e., the economies of scale of emerging technologies depends on the total number of users choosing the same technology. If more stakeholders are involved, it will make the costs of changing structures and processes worthwhile.
3	Assess project performance	There has been plenty of evidence that many financial risks are created in the early stage of new technology adoption, particularly when stakeholders do not support a reliable cost-benefit analysis on construction automation projects. Stakeholders should regularly assess project performance to evaluate the benefits being gained from automating parts of the construction process. This, of course, includes clearly defining the benefits for each of the stakeholders. For example, a client gains from the use of building information modelling when complex designs are to be done as it is easier, and therefore less costly to incorporate changes. It is only with this assessment that it will become clear that the early costs of automation implementation are worthwhile.
4	Develop building information protocols	The development of standardized building information protocols would be beneficial to enabling fluid information exchange between stakeholders. For example, problems often appear when responsibility for an information model is transferred from designers to contractors. As construction projects move from the preliminary design phase to delivery, stakeholders should form a set of policies and procedures for information manipulation to protect data and delimitate responsibilities, specifically determining the scope and details of information, the use of information and organization of information.
5	Develop appropriate legal contracts	The development of appropriate legal contracts would be beneficial to enabling secure information exchange between stakeholders. The most important step for setting up an adapted legal contract is the assignment of new roles to each participant (e.g., BIM system integrator or BIM information manager [80]), corresponding to an innovative contract model and a common data platform. Collaborative decision-making and control, dispute resolution, multi-party contract with clear labilities should be addressed through the application of a common building information protocol and a legal contract. Appropriate legal contracts would enable all stakeholders to contribute to the best of their abilities to the creation, modification and review of building information.
6	Integrate building information through standard data schema	The most significant division of construction process is in the separation of the design and construction phase. To ensure the upstream design information is seamlessly delivered to the downstream construction expertise, a standards data schema is needed among different parties. A standard data schema is an information exchange format to organize and carry data of building geometry and material properties. There are several prevalent data schema in use, such as IFC, gbXML, COBie. However, none of them is easily synchronized on multiple model platforms. A standard data schema should be developed to allow object-level coordination across heterogeneous building information models. It will also allow construction automation project stakeholders to gain benefits from efficient information sharing and collaborative working processes.

mining on scientific literature and social media with respect to the use of automation technologies in construction was accomplished. In research, it was found that scientific research work was mainly focused on developments that can be grouped as 1) Construction Robots and Automation Systems, 2) Construction Managerial Objectives, and 3) Building Information Modelling Based Collaborations. In industry, an active interaction was found between company investment on technologies, market share and the final construction product. It was also found that there is a lack of integration of various automation technologies, resulting in problems regarding information interoperability, information security and contractual responsibility. Major benefits and challenges were discovered by contextual interpretation of text. In general, the automation of construction provides improvements in 1) the efficiency of work processes with respect to different objectives, 2) the communication and collaboration between stakeholders, and 3) a potential to increase market scale. The challenges with which the industry is faced are: 1) a lack of maturity of use of information, 2) a lack of company investment, and 3) a lack of economic competition.

In order to realize the benefits from making use of construction automation and to overcome the challenges to do so, the suggestions proposed are 1) Reengineer business structures and processes, 2) Increase the scale of adoption, 3) Assess project performance, 4) Develop building information protocols, 5) Develop appropriate legal contracts, and 6) Integrate building information through standard data schema. By acting on these suggestions, the construction industry will help to accelerate the automation of their processes and the gains in terms of productivity, which can be translated in to winning market share, increasing profits or both.

It should be highlighted that the focus of this research is to provide an overall picture of construction automation; however, some perspectives that were not obvious from the text mining results (but from details in the literature) are still worth mentioning. For example, besides the need of scale of adoption and standardization, complexity and uniqueness is an important issue to be addressed during the implementation. Mass customization, rather than mass production, is non-negligible considering the uniqueness of each construction project. It is foreseeable, although not well-known so far, that BIM's parametric capacity on modelling complex shapes and the diversity of robot-driven operations will join in force to contribute to construction automation particularly on mass customization of projects. It is difficult to observe these hidden issues from the text mining results, but they are tightly associated with the main trends identified as a premise to understand construction automation. While construction automation is taking place widely nowadays, it is imperative from the start to build the common knowledge to clarify the major benefits and potentials with the help of data-driven review methods, thereby to establish a comprehensive understanding of construction automation.

Appendix A

Table 11
144 Web of Science indexed journals related to construction automation.

Item no.	Name of journal	Total number of selected papers
1	Automation in Construction	211
2	Journal of Construction Engineering and Management-ASCE	78
3	Journal of Management in Engineering	26
4	Journal of Information Technology in Construction	25
5	Journal of Civil Engineering and Management	24
6	Building and Environment	19
7	KSCE Journal of Civil Engineering	16
8	Engineering Structures	14
9	Canadian Journal of Civil Engineering	12
10	Engineering Construction and Architectural Management	12
11	ICSDEC 2016 - Integrating Data Science, Construction and Sustainability	11
12	5th Creative Construction Conference (CCC 2016)	10
13	Bauingenieur	10
14	Bautechnik	10
15	Building Research and Information	10
16	Architectural Engineering and Design Management	9
17	Journal of Asian Architecture and Building Engineering	9
18	Structural Analysis of Historical Constructions, Vols 1–3	9
19	Built Environment Project and Asset Management	8
20	AEI 2015: Birth and Life of the Integrated Building	6
21	Creative Construction Conference 2014	6
22	First International Conference on Improving Construction and Use Through Integrated Design Solutions	6
23	Proceedings of the Institution of Civil Engineers-Civil Engineering	6
24	Creative Construction Conference 2015, Selected Papers	5
25	Journal of Performance of Constructed Facilities	5
26	Structure and Infrastructure Engineering	5
27	World Multidisciplinary Civil Engineering-Architecture-Urban Planning Symposium 2016, WMCAUS 2016	5
28	Architecture, Building Materials and Engineering Management, Pts 1–4	4
29	Revista de la Construccion	4
30	Structural Design of Tall and Special Buildings	4
31	System-Based Vision for Strategic and Creative Design, Vols 1–3	4
32	Construction Congress VI, Proceeding: Building Together for a Better Tomorrow in an Increasingly Complex World	3
33	EURODYN 2014: IX International Conference on Structural Dynamics	3
34	Informes de la Construccion	3
35	International Journal of Architectural Heritage	3
36	Journal of Building Physics	3
37	Modern Building Materials, Structures and Techniques	3
38	Proceedings of the Institution of Civil Engineers-Structures and Buildings	3
39	Proceedings of the Twelfth East Asia-Pacific Conference on Structural Engineering and Construction (EASEC12)	3
40	Structural Concrete	3
41	Structures and Architecture: Concepts: Applications and Challenges	3
42	Tunnelling and Underground Space Technology	3
43	Advances in Civil Engineering II, PTS 1–4	2
44	Advances in Engineering Structures, Mechanics & Construction, Proceedings	2
45	Advances in Structural Engineering	2
46	Building Simulation Applications (BSA 2013)	2
47	Construction and Project Management, ICCPM 2011	2
48	Contributions to Building Physics	2
49	Gradevinar	2
50	Ideas to Impact: How Building Economic Standards Keep You on Track	2
51	Indoor and Built Environment	2
52	International Journal of Civil Engineering	2
53	Journal of Aerospace Engineering	2
54	Journal of Architectural Engineering	2
55	Journal of Constructional Steel Research	2
56	Journal of Infrastructure Systems	2
57	Journal of Structural Engineering	2

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Table 11 (*continued*)

Item no.	Name of journal	Total number of selected papers
58	Journal of the International Association for Shell and Spatial Structures	2
59	Proceedings of CRIOCM 2006 International Research Symposium on Advancement of Construction Management and Real Estate, Vols 1 and 2	2
60	Proceedings of the Second International Postgraduate Conference on Infrastructure and Environment, Vol 1	2
61	Stahlbau	2
62	Structural Control & Health Monitoring	2
63	Structural Survey	2
64	Structures Congress 2015	2
65	Thin-Walled Structures	2
66	15th International Scientific Conference Underground Urbanisation as a Prerequisite for Sustainable Development	1
67	6th International Symposium of Asia Institute of Urban Environment: Energy Conservation and Carbon Off in Asia City	1
68	8th International Cold Climate HVAC Conference	1
69	Advances in Civil and Structural Engineering III, Pts 1–4	1
70	Advances in Structural Engineering, Pts 1–3	1
71	Architecture Civil Engineering Environment	1
72	Archives of Civil Engineering	1
73	Ashrae Transactions 2006, Vol 112, Pt 1	1
74	Baltic Journal of Road and Bridge Engineering	1
75	Big Digs Around the World	1
76	Bridge Maintenance, Safety, Management and Life Extension	1
77	Buildings	1
78	Challenges for the 21st Century, Vol I: Investigations, Planning and Design/Underground Space Use/Support and Lining of Tunnels	1
79	Challenges for the 21st Century, Vol. 2: Communication Tunnels/Miscellaneous Including Water Tunnels/ Mechanised Tunnelling	1
80	Civil Engineering and Environmental Systems	1
81	Civil Engineering and Urban Planning III	1
82	Civil Engineering and Urban Planning IV	1
83	Civil Engineering in China - Current Practice and Research Report: Proceedings of the 2nd International Conference on Civil Engineering	1
84	Computer-Aided Architectural Design Futures (CAAD Futures) 2007	1
85	Construction Innovation and Global Competitiveness, Vols 1 and 2: the Organization and Management of Construction	1
86	Construction Materials and Structures	1
87	Dynamics of Civil Structures, Vol 2	1
88	Earthquake Engineering & Structural Dynamics	1
89	Earthquake Spectra	1
90	Earthquakes and Structures	1
91	Fourth Conference on Tall Buildings in Seismic Regions, Proceedings: Tall Buildings for the 21st Century	1
92	Geo-China 2016: Emerging Technologies in Tunnel Engineering, Modelling, Design, Construction, Repair, and Rehabilitation	1
93	Geotechnical Aspects of Underground Construction in Soft Ground	1
94	Harvesting and Managing Knowledge in Construction: From Theoretical Foundations to Business Applications	1
95	II International Conference on Concrete Sustainability - ICCS16	1
96	Innovation & Sustainability of Structures, Vols 1 and 2	1
97	Intelligent Buildings International	1
98	International Journal of Steel Structures	1
99	Journal of Building Engineering	1
100	Journal of Civil Structural Health Monitoring	1
101	Journal of Structural Engineering-ASCE	1
102	Journal of Surveying Engineering	1
103	Journal of Surveying Engineering-ASCE	1
104	Life-Cycle of Structural Systems: Design, Assessment, Maintenance and Management	1
105	Modern Building Materials, Structures and Techniques, 10th International Conference 2010, Vol II	1
106	Modern Earth Buildings: Materials, Engineering, Construction and Applications	1
107	PCI Journal	1
108	Periodica Polytechnica-Civil Engineering	1
109	Pipeline Safety, Reliability, and Rehabilitation	1
110	Proceedings of Shanghai International Conference on Technology of Architecture and Structure, Pt II	1

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Table 11 (*continued*)

Item no.	Name of journal	Total number of selected papers
111	Proceedings of the 8th International Symposium on Heating, Ventilation and Air Conditioning, Vol 1: Indoor and Outdoor Environment	1
112	Proceedings of the First International Postgraduate Conference on Infrastructure and Environment	1
113	Proceedings of the Institution of Civil Engineers-Forensic Engineering	1
114	Proceedings of the Institution of Civil Engineers-Municipal Engineer	1
115	Proceedings of the Thirteenth International Symposium on Structural Engineering, Vols 1 and II	1
116	Profitable Partnering in Construction Procurement	1
117	Progress in Industrial and Civil Engineering, Pts. 1–5	1
118	Recent Developments in Building Diagnosis Techniques	1
119	Recent Progress in Steel and Composite Structures	1
120	Reducing Risk From Extreme Events	1
121	Research in Building Physics	1
122	Research on Building Physics	1
123	Revista Ingenieria de Construccion	1
124	Rock Mechanics for Industry, Vols 1 and 2	1
125	Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2015	1
126	Seventh International Cold Climate HVAC Conference	1
127	Shotcrete Technology	1
128	Slovak Journal of Civil Engineering	1
129	Smart Structures and Systems	1
130	SSE '09: Proceedings of the 11th WSEAS International Conference on Sustainability in Science Engineering	1
131	Steel - a New and Traditional Material for Building	1
132	Structural Engineering International	1
133	Structural Safety	1
134	Structural Studies, Repairs, and Maintenance of Heritage Architecture IX	1
135	Structures	1
136	Structures in Fire: Proceedings of the 6th International Conference	1
137	Sustainable Cities Development and Environment Protection, Pts 1–3	1
138	Sustainable Development of Urban and Rural Areas	1
139	Tall Buildings: From Engineering to Sustainability	1
140	Underground Space - the 4th Dimension of Metropolises, Vols 1–3	1
141	XV International Conference Topical Problems of Architecture, Civil Engineering, Energy Efficiency and Ecology - 2016	1
142	XXIII R-S-P Seminar, Theoretical Foundation of Civil Engineering (23RSP) (TFOCE 2014)	1
143	XXIV R-S-P Seminar, Theoretical Foundation of Civil Engineering (24RSP) (TFOCE 2015)	1
144	XXV Polish - Russian - Slovak Seminar -Theoretical Foundation of Civil Engineering	1
	Grand total	741

Appendix B

Table 12
50 social media webpages related to construction automation.

Item no.	Name of webpage	Website	Applicable for data retrieval?	Category
1	Engineering News Record (ENR)	http://www.enr.com/	NO	Online news
2	The Construction Index	http://www.theconstructionindex.co.uk/all-construction-news	YES	Association webpage
3	Reddit Construction Blog	https://www.reddit.com/r/Construction/	YES	Blog
4	Buildings: Smart Facility Management	http://www.buildings.com/magazine/issue/672	NO	Online news
5	Equipment World	http://www.equipmentworld.com/	YES	Online news
6	Construction News (CN)	https://www.constructionnews.co.uk/	YES	Online news
7	Construction Enquirer	http://www.constructionenquirer.com/	YES	Online news
8	Construction Dive	http://www.constructiondive.com/	YES	Online news
9	Contractor Magazine	http://www.contractormag.com/	YES	Online news
10	Professional Builder - Housing Zone	https://www.probuilder.com/	YES	Online news
11	Sourceable	https://sourceable.net/	YES	Blog
12		http://blog.capterra.com/articles/construction-software/	YES	Blog

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Table 12 (*continued*)

Item no.	Name of webpage	Website	Applicable for data retrieval?	Category
	Capterra Construction Management Blog			
13	Tiny House Blog	http://tinyhouseblog.com/	NO	Blog
14	Construction Junkie Blog	http://www.constructionjunkie.com/	YES	Blog
15	Construction Technology Blog	https://conappguru.com/blog/	YES	Blog
16	Sage Construction and Real Estate Blog	http://blog.sagecre.com/	YES	Blog
17	Commercial Construction & Renovation	http://www.ccr-mag.com/	NO	Online news
18	ConstructConnect	http://www.constructconnect.com/	YES	Association webpage
19	Aconex	https://www.aconex.com/blogs/	NO	Association webpage
20	Sandvik Construction	http://construction.sandvik.com/news-media/	NO	Association webpage
21	Build Blog	http://blog.buildllc.com/	YES	Blog
22	Dexter + Chaney Blog	http://www.dexterchaney.com/news/blog/	NO	Blog
23	ModSpace Blog – Construction News, Updates & Insights	http://blog.modspace.com/	NO	Blog
24	Construction Specifier (The official magazine of CSI)	https://www.constructionspecifier.com/	YES	Online news
25	THELIENZONE	https://www.thelienzone.com/	NO	Association webpage
26	Extranet Evolution	http://extranetevolution.com/tag/eadoc/	NO	Blog
27	AUTODESK - Industries	https://www.autodesk.com/solutions/bim/construction-management-software	YES	Association webpage
28	CONSTRUTECH	https://constructech.com/	YES	Online news
29	Talking Construction	http://talkingconstruction.gateleyplc.com/	YES	Blog
30	SHIEL SEXTON Blog	http://www.shielsexton.com/blog/	NO	Blog
31	The UK Construction Blog	http://ukconstructionblog.co.uk/	YES	Blog
32	Winnipeg Construction Association	winnipegconstruction.ca/news	NO	Association webpage
33	WOHLSEN CONSTRUCTION	http://www.wohlsenconstruction.com/	NO	Association webpage
34	GRANGER Blog	http://www.grangerconstruction.com/blog/	YES	Blog
35	The Construction History Society (CHS)	http://www.constructionhistory.co.uk/	NO	Association webpage
36	Alberta Construction Association	http://albertaconstruction.net/	NO	Association webpage
37	Planting Acorns	http://plantingacorns.com/	YES	Blog
38	Hard Hat Chat	http://commercialconstructionblog.com/	NO	Blog
39	Stahl Construction	http://www.stahlconstruction.com/	NO	Association webpage
40	Mates in Construction	http://matesinconstruction.org.au/	NO	Blog
41	McKinsey&Company: Capital Projects and Infrastructure	http://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights	YES	Online news
42	OAC Services	http://oacservicesinc.com/who-we-are/blog/	NO	Association webpage
43	Jetson Green Projects	http://www.jetsongreen.com/	NO	Association webpage
44	BuildingRadar	https://buildingradar.com/de/	YES	Blog
45	Construction Industry Federation	http://cif.ie/news-feed/blog.html	YES	Association webpage
46	CORE Construction	http://www.coreconstruction.com/news/	NO	Association webpage
47	Digital Construction News	http://digitalconstructionnews.com/	YES	Online news
48	Building.co.uk	http://www.building.co.uk/	YES	Online news
49	Lean Construction Blog	http://leanconstructionblog.com/	YES	Blog
50	Builder	http://www.builderonline.com/	YES	Online news

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.autcon.2018.05.028.

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