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A bibliometric study of the recent literature

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Abstract

Purpose – The emergent field of Internet of Things (IoT) has been evolving rapidly with a geometric growth in the number of academic publications in this field. The purpose of this paper is to review the literature of IoT in past 16 years using rigorous bibliometric and network analysis tools, offering at the same time future directions for the IoT research community and implications for managers and decision makers.

Design/methodology/approach – The authors adopted the techniques of bibliometric and network analysis. The paper reviewed the articles published on IoT from 2000 to 2015.

Findings – This study identifies top contributing authors; key research topics related to the field; the most influential works based on citations and PageRank; and established and emerging research clusters. Scholars are encouraged to further explore this topic.

Research limitations/implications – This study focusses only on vision and applications of IoT. Scholars may explore various other aspects of this area of research.

Originality/value – To the best of authors' knowledge, this is the first study to review the literature on IoT by using bibliometric and network analysis techniques. The study is unique as it spans a long time period of 16 years (2000-2015). The study proposes a five-cluster classification of research themes that may inform current and future research in IoT.

Keywords Vision, Internet of Things, Bibliometrics, Applications, Network analytics

Paper type Literature review

1. Introduction

Recent years have witnessed the growing use of internet as billions of people browse the web to access multimedia content and services, send and receive electronic mails, play games, and perform various tasks. This use creates a global platform for machines

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and smart objects to communicate, dialogue, compute, and coordinate (Miorandi *et al.*, 2012), which in turn builds up a strong connection among the users of smart devices worldwide. Apart from connecting the users to the internet, these devices play a crucial role in linking up the physical world with the cyber world (Conti *et al.*, 2012). This has given birth to the next generation of embedded ICT systems, commonly known as cyber-physical systems (CPS) (Poovendran, 2010; Park *et al.*, 2012), which integrate computational devices with the physical environment. CPS is composed of four technologies: automation of knowledge work, Internet of Things (IoT), advanced robotics, and autonomous/near-autonomous vehicles. Looking at the economic value generated by these technologies, it can be clearly observed that IoT, with an estimated value of 36 trillion of dollars, creates the highest economic impact (McKinsey Global Institute, 2013).

The term "IoT" came into existence when Kevin Ashton used it for the first time in 1999 to represent the globally emerging internet-based information service architecture (Ashton, 2009). Weber (2009) defined IoT as "an emerging global, Internet-based information service architecture facilitating the exchange of goods in global supply chain networks […] on the technical basis of the present Domain Name System; drivers are private actors." IoT facilitates a safe and trustworthy way of exchanging information related to goods and services in a global supply chain. It acts as a pillar for ubiquitous computing that opens the door for smart environments to spot and track items, and collect information from the internet for their proper functioning. In doing so, members of MIT Auto-ID Center developed Electronic Product Code that serves as a universal identifier for any specific item (Gama *et al.*, 2012; EPC Global Inc., 2011). The main objective behind this development was to spread awareness about the use of radio-frequency identification (RFID) globally. But, these days, the idea of "Thing" is not only restricted to RFID. It has expanded to include any real or physical object (e.g. RFID, sensor, actuator, smart item), "spime" data object as well as any virtual or digital system, which is capable of moving in time and space. These entities can be identified uniquely through the identification details (numbers, names, and/or location addresses) assigned to them. Thus, the "Thing" can be read, recognized, located, addressed and controlled effortlessly by using Internet (Borgia, 2014).

IoT has simplified our day-to-day lives by creating smart objects, applications, and services, which ensure safety and security during the information exchange process. Indeed, IoT has the ability to influence economic activity across industries and affect their strategic decisions, investments, and productivity (Borgia, 2014). Mandel (2014) visualized that US GDP will approximately increase by 2-5 percent by the end of 2025. At present, digital industries contribute about 20 percent of the GDP while the rest 80 percent comes mainly from physical industries, i.e., agriculture, construction, manufacturing, energy, transportation, and healthcare. Therefore, IoT aims to transform the way in which physical industries do business by connecting them to the computerized world.

In recent years, scholars (Borgia, 2014; Whitmore *et al.*, 2014; Madakam *et al.*, 2015; Russo *et al.*, 2015) have attempted to review the literature on IoT by focussing on its vision, concepts, applications and features. Although these studies have provided insight into the field of IoT, they have not conducted additional analysis via rigorous bibliometric and network analytics tools. Such an analysis can help in refining the established and emerging areas of research, and in researchers acknowledging the different schools of thought and relevant applications of IoT. Moreover, the meaning of the term "IoT" itself is continuously evolving since the technologies and ideas which drive it are also changing. These challenges signify the reason for considering IoTs vision and applications in our study.

To address this gap, this study reviews the literature from 2000-2015 on IoT using bibliometric and network analytics tools. We review, refine, and analyze a set of 1,777 articles to obtain the most influential works, research themes, and researchers. We propose a five-cluster classification of research themes that provides additional insights on the current field and potential future research directions have been obtained.

In the next section, we review the literature on vision and applications of IoT which is followed by methodological considerations and initial results of our review. Then, we present a detailed analysis using the technique of bibliometric and network analysis. The paper ends with conclusion, limitations and future research directions.

2. Review of the literature on IoT

This section is broadly divided into two major areas of literature, that is, vision of IoT, and applications of IoT.

2.1 IoT: vision

The phrase "IoT" originated at MIT Auto-ID Center and Kevin Ashton was the first to introduce it in 1999 during a presentation held at Procter & Gamble (Ashton, 2009). Ashton visualized that the physical world can be connected to the internet via sensors and actuators which are capable of providing real time information and hence benefit our lives in several ways. This concept came into public eye when International Telecommunications Union (ITU) published its first report on this subject in 2005. By adopting an integrated and comprehensive approach, ITU suggested that "Internet of Things will connect the world's objects in both a sensory and intelligent manner through combining technological developments in item identification ('tagging things'), sensors and wireless sensor networks ('feeling things'), embedded systems ('thinking things') and nanotechnology ('shrinking things')". In 2009, the Cluster of European Research projects (CERP) gave its vision on IoT by combining different ideas and technical components of pervasive computing, ubiquitous computing and ambient intelligence. They defined IoT as "a dynamic global network infrastructure with self-capabilities based on standard and interoperable communication protocols where physical and virtual 'things' have identities, physical attributes, virtual personalities and use intelligent interfaces, and are seamlessly integrated into the information network" (Vermesan *et al.*, 2011).

The RFID group views IoT as "the worldwide network of interconnected objects uniquely addressable based on standard communication protocols." In their work on IoT, the CERP expected "Things" to "become active participants in business, information and social processes where they are enabled to interact and communicate among themselves and with the environment by exchanging data and information 'sensed' about the environment, while reacting autonomously to the 'real/physical world' events and influencing it by running processes that trigger actions and create services with or without direct human intervention." CERP's vision of IoT has been extended by Uckelmann *et al.* (2011) to form a blend of two different concepts: web 2.0 and self-sustainability. Specifically, web 2.0 technology uses simple and instinctive interfaces that enables users to make their web contributions, irrespective of their technical capabilities. This interaction between Things and users is of central importance because it will be one of the key issues in the future Web of Things.

Uckelmann *et al.* (2011) combined these concepts and gave their own vision of IoT: "the future Internet of Things links uniquely identifiable things to their virtual representations in the internet containing or linking to additional information on their identity, status, location, or any other business, social or privately relevant information at a financial or non-financial pay-off that exceeds the efforts of information provisioning and offers information access to non-predefined participants. The provided accurate and appropriate information may be accessed in the right quantity and condition, at the right time and place at the right price. The Internet of Things is not synonymous with ubiquitous/pervasive computing, the Internet Protocol (IP), communication technology, embedded devices, its applications, the Internet of People or the Intranet/Extranet of Things, yet it combines aspects and technologies of all of these approaches."

Atzori *et al.* (2010) pin pointed three viewpoints for defining IoT: things-oriented (sensors), internet-oriented (middleware), and semantic-oriented (knowledge). From a things-oriented perspective, IoT is not merely the identification of objects but provides a much broader vision. The internet-oriented perspective emphasizes that efficient links should be established between devices by taking advantage of the IP protocol and focussing on the networking paradigm. The semantic-oriented perspective aims at using semantic technologies for handling the large amount of data which is being generated from various IoT objects (Borgia, 2014). With reference to Atzori's vision of IoT, Gubbi *et al.* (2013) noted that benefits of IoT can be realised only when these three paradigms coincide. In the context of smart environments, Gubbi *et al.* (2013) defined IoT as the "Interconnection of sensing and actuating devices providing the ability to share information across platforms through a unified framework, developing a common operating picture for enabling innovative applications. This is achieved by seamless ubiquitous sensing, data analytics and information representation with Cloud computing as the unifying framework." Recently, Borgia (2014) suggested that a complete vision of IoT can be observed via 6As, that is, "Anytime-Anywhere", "Anyone-Anything," and "Any path/network-Any service."

2.2 IoT: applications

Following our review, we have categorized IoT applications into four major domains, that is, "Industry domain," "Healthcare domain," "Smart environments domain," and "Personal and Social domain."

2.2.1 Industry domain. The real time information provided by RFID and near field communication (NFC) technology helps in keeping track of every activity in a supply chain, starting from product design to distribution and then final delivery of products to the end users. In doing so, organizations can obtain accurate and timely information related to the products that can help organizations respond to the market changes in shortest possible time. As an outcome, smart/advanced organizations (e.g. Wal-Mart and Metro) can meet changing customer requests promptly and with zero safety, stock whereas traditional organizations take approximately 120 days to meet this demand (Yuan *et al.*, 2007). According to Karpischek *et al.* (2009), shop assistants can provide up-to-date product information to the customers by having real time access to the ERP system. The real time information provided by RFID-based objects and smart shelves helps smart systems in reducing the level of material wastage, thereby saving cost and increasing profit margin. IoT applications can also be seen in the automobile industry. For instance, sensors installed in the vehicles can monitor its each and every detail (such as, tire pressure, motor data, fuel consumption, location, speed, distance from other vehicles) and then transfer the gathered data to the central system (Hank *et al.*, 2013).

2.2.2 Healthcare domain. IoT has several potential benefits in medical and healthcare sectors. Smart tracking devices help in detecting a moving person or item. IoT involves real time location tracking as well as movement tracking at choke points, where the former may be used to identify and track the location of a patient in a hospital, and the latter may help in monitoring the movement of patients through entry and exit points of a ward. In addition, these devices help in continuously managing the inventory status and monitoring the movement of materials within a hospital (Atzori *et al.*, 2010). Other relevant applications aim at identifying patients and infants and at avoiding incidents such as infant mismatching, wrong dosage of medicines, and incorrect procedures. These incidents can be minimized by maintaining an electronic medical record system that contains information of all in- and out-patients. In fact, patients' conditions can be analyzed by using sensor devices that help in obtaining real time information related to patients' health. The data generated through these devices can be then transferred to medical staff for further diagnosis by using communication technologies (such as, Bluetooth, Zig Bee, Wireless HART, and ISA100).

2.2.3 Smart environments domain. IoT may enhance the quality of people's life in several ways. Nowadays, vehicles with mobile sensors get detailed information related to traffic density or surface conditions of the road as compared to the fixed sensors which were used earlier (Ganti *et al.*, 2011). Moreover, the data gathered from these sensors can be then transmitted to control centers via vehicle-to-vehicle and vehicle-to-infrastructure communication systems. Additionally, Polycarpou *et al.* (2013) identified the application of IoT in parking systems. Its application may help drivers in finding a parking lot as per their convenience and preference, thereby saving time and fuel, while bringing down the level of carbon footprint. Sensors located at parking lots ease the work of municipalities by detecting the illegally parked vehicles which can be then towed away. The payment systems at toll booths and parking lots can be made easy and smooth. The drivers may adopt NFC technology in their mobile phones for payments at parking and use RFID-based electronic system for toll collection (Qadeer *et al.*, 2009). In addition, IoT may find its applications in transforming the traditional gym to smart gym. The gym trainer can feed the exercise description in the training machine for each trainee. The RFID tag in the machine can then automatically identify the trainee and monitor the health parameters throughout the training session (Atzori *et al.*, 2010). Further applications can be observed in entertainment and tourism sectors. In this regard, Amato *et al.* (2012) mentioned that smart phone users can obtain information related to monuments and tourist places.

2.2.4 Personal and social domain. Many benefits are provided by IoT to the personal and social domain. A broad range of applications can be generated by combining sensors and smart devices (e.g. broadband gateways, mobile phones, laptops, PCs, TV, speakers, appliances, plugs, surveillance cameras, and lights). Computerized home systems enable residents to control every activity remotely via web applications. Chen *et al.* (2013) suggested that users can live a comfortable life if their smart phones act as a remote control for managing all the household appliances and their habits are continuously monitored by tracking their mobile phones. As an example, by analyzing the information flow, a system can learn a person's schedule, and thus perform automatic functions such as unlocking the door and switching on the lights.

In the context of loss and theft, a web-based RFID application acts as a search engine for things. It assists users in finding the lost objects by following their previous location records. Additionally, it alerts the user if any specific object is displaced from its original position. For instance, the user may receive an SMS via application if the stolen objects are taken out of any restricted area. Moreover, social domain applications allow easy communication among people so that they can build and maintain strong social relationships. Social networking enables an automatic update of our social activities on social networking sites such as Twitter and Facebook.

3. Research methodology

Literature review maps and assesses the relevant literature in order to find out the possible research gaps which would be beneficial in further strengthening of the knowledge (Tranfield *et al.*, 2003). In this paper we followed Saunders *et al.* (2009) and their conceptualisation of literature review as an adaptive cycle which involves the process of defining relevant keywords, conducting literature search and finally, performing analysis; the approach proposed by Rowley and Slack (2004): scanning documents, making notes, structuring the literature review, writing the literature review, and building the bibliography; and Fahimnia *et al.* (2015) and their review of green supply chain literature using bibliometric and network (citation and co-citation) analysis.

3.1 Keyword search and data collection

The articles were collected using Scopus database only. The reason is that Scopus is the largest abstract and citation database covering more than 20,000 peer-reviewed journals in the fields of science, technology, medicine, social sciences, and arts and humanities, which belong to, inter alia, the publishing houses of Elsevier, Emerald, Informs, Taylor and Francis, Springer, and Inderscience (Fahimnia *et al.*, 2015). According to Yong-Hak (2013), Scopus database is more comprehensive than Web-of-Science (WoS) database because WoS includes only ISI indexed journals which is further limited to only 12,000 titles. In fact, Chicksand *et al.* (2012) noted that Scopus is a good source of supply chain peer reviewed articles.

Keeping in mind the objective of this paper, we chose the keywords which fully cover IoT vision and applications. Hence, we used the following keywords for the process of data collection: "Internet of Things", "Vision of Internet of Things," and "Applications of Internet of Things." Through these keywords, three different combinations were made: IoT, Vision and IoT, and Applications and IoT. We searched for the aforementioned keywords in "title, abstract, keywords" of articles belonging to Scopus database. The initial search resulted in 1,777 articles. The number of articles obtained for each combination of keywords is shown in Table I. The results containing

Search keywords	Search results (no. of papers)
Internet of Things	986
Vision and IoT	426
Applications and IoT	365
Total	1,777

Table I.
Initial results

the necessary information such as title of the paper, authors' names and affiliations, abstract, keywords, and references, were then saved in RIS format.

While refining the search results, we removed the duplicates as there is a possibility that few articles may belong to more than one combination of keywords. On eliminating such duplications, we were left with 1,556 papers. Since Ramos-Rodríguez and Ruiz-Navarro (2004) categorized articles and reviews as "certified knowledge," we restricted ourselves to only scientific publications (articles and reviews) that appeared in peer reviewed journals. Unpublished articles, working papers, and magazine articles were excluded during data purification process. This search resulted in 923 relevant documents, published during 16-year period, i.e., 2000-2015. Table II shows the breakdown of refined search results for each of the three combination of keywords. For carrying out these refinements in the RIS file, Endnote bibliography software was used. Then, the final RIS data file was stored for future analysis.

In the next step, we excluded those articles that were not included in the well-known journals. It was found that these journals have published 146 articles. The number of articles published per journal is shown in Table III.

Figure 1 demonstrates the changing pattern of publications in each year, starting from 2009 to 2015. It can be clearly seen from the figure that the number of publications on IoT before 2013 increased slowly, but in the last three years, it has been increasing dramatically.

3.2 IoT: influence of researchers

To analyze the influence of particular researchers, the author field was first extracted from the RIS data file and then the frequency of occurrence of each of these

Search keywords	Search results (no. of papers)
Internet of Things	458
Vision and IoT	270
Applications and IoT	195
Total	923

Table II. Refined search results

Journals	No. of articles
Personal and Ubiquitous Computing	25
International Journal of Production Economics	11
International Journal of Production Research	5
Computers and Security	6
IEEE Security and Privacy	5
IEEE Internet of Things Journal	42
Network Security	7
Computer Law and Security Review	9
Electronic Design	13
Journal of Information and Computational Science	9
Logistics Journal	6
Computer Networks	6
Future Generation Computer Systems	2
Total	146

Table III. Journal wise publication breakdown table

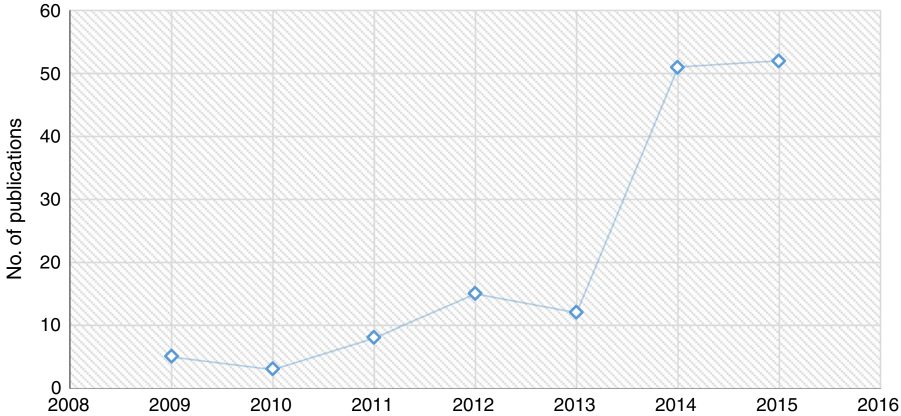

Figure 1.
Distribution of articles published (from 2008 to 2015)

authors was noted. Table IV shows the top ten contributing authors along with their number of publications. It can be clearly observed that Weber and Wang with six publications dominate the list, and is followed by Jara with four publications.

3.3 Keyword statistics

A similar analysis was performed in order to identify the most commonly used words in the paper titles and the list of keywords. Tables V and VI, show the top 20 keywords used in the paper titles and most popular keywords from the list of keywords, respectively. By comparing these two tables, it can be observed that there is a uniformity in the use of keywords in the title and the list of keywords. For instance, in both tables the top keywords include a combination of IoT, vision, and its applications. It is to be noted here that the most popular keywords which occur in Table V are actually the search keywords which we chose for this study.

3.4 Data analysis

The output of our data analysis were used to conduct our analysis with bibliometric and network analytics tools. To conduct bibliometric analysis, different software packages are available with own capabilities and limitations. The most commonly used software for this purpose are "Publish or Perish," "HistCite," and "BibExcel." There were two main reasons for selecting BibExcel software in this study.

Table IV.
Top ten contributing authors

Author	Number of published articles
R.H. Weber	6
H. Wang	6
A.J. Jara	4
L. Gu	3
J. Yang	3
M. Ten Hompel	3
F. Tao	2
J. Li	2
J. Ferrari	2
G.Q. Huang	2

Word	Frequency
Internet of Things	114
Internet	89
IoT	87
Internet of Thing (IoT)	26
Radio frequency identification (RFID)	23
Wireless sensor networks	23
Security	19
RFID	14
Vision	12
Authentication	12
Cloud computing	12
Ubiquitous computing	11
Supply chain	11
Supply chain management	10
IOT	10
Network security	10
Mobile security	9
Information services	9
Semantic web	8
Algorithms	8

Table V. Top 20 keywords search results

Word	Frequency
Things	68
Internet	58
IoT	10
RFID	10
Supply	10
Approach	10
Applications	10
Service	9
Vision	8
Privacy	8
Systems	8
New	8
Information	8
Data	8
Management	8
Networks	7
Chain	7
Security	7
Architecture	7
Design	7

Table VI. Top 20 commonly used words in titles

First, it is highly flexible in altering the data imported from databases such as Scopus and WoS, and second, it is able to offer an extensive data analysis which can be further used by network analysis tools. Other tools, such as HistCite can only work with data imported from WoS while Publish or Perish works with Google Scholar and

Microsoft Academic Search. It is worth mentioning here that apart from BibExcel, the other tools do not generate data for future network analysis.

The analysis of data for the bibliometric analysis was conducted in two stages. In the first stage, bibliometric analysis was performed using BibExcel software which provides data statistics containing author, affiliation, and keyword statistics. We opted for BibExcel software because it is flexible enough to handle huge amount of data and is also compatible with other applications such as, Excel, Pajek, and Gephi (Persson *et al.*, 2009). The data entered in BibExcel is in RIS format and contains all the necessary bibliographic information related to the papers. In our analysis, we mainly concentrated on information regarding authors, title, journal, publication year, keywords, affiliations, and references. During these analyses, the RIS file is converted into different formats, and as a result, various file types are produced. To get a thorough knowledge about the processes and applications of BibExcel, readers may refer to Paloviita (2009) and Persson *et al.* (2009).

In the second stage, network analysis was done which makes use of the data prepared in BibExcel software. To conduct this analysis, Gephi was chosen. Besides Gephi, the most widely used tools for conducting any network analysis are Pajek (Batagelj and Mrvar, 2011), VOSviewer (van Eck and Waltman, 2013), and HistCite Graph Maker. For carrying out this study, we preferred Gephi because it provides flexible visual aids, powerful filtering techniques, inherent toolkit for network analysis and capability to handle different data formats. In addition, the other network analysis software lack one or the other property of Gephi. For instance, HistCite graph maker accepts WoS data files, Pajek can only handle. Net files and VOSviewer has limited tools for performing network analysis. Gephi is an important open source software package which makes use of a 3D render engine to make large networks in real time (Gephi, 2013). Owing to its flexible and multi-task architecture, it can easily handle complicated data sets and generate insightful visualization. Bastian *et al.* (2009) noted that Gephi provides "easy and broad access to network data and assist in specializing, filtering, navigating, manipulating and clustering of data." Before going for visualization and mapping in Gephi, a data set containing published papers, which is denoted by nodes, and their citations, represented by the arcs or edges between the nodes, must be prepared. Thus, the bibliographic data which is downloaded from Scopus and saved in RIS format cannot be used directly, and in this situation, BibExcel software acts as a mediator which reformats the original data file to graph data set or .NET file. This file is saved for future network analysis in Gephi.

3.5 Network analysis

3.5.1 Citation analysis. The aim of citation analysis is to examine the citation frequency of a particular document. Garfield (1972) mentioned that the total number of citations on a scientific journal is an indication of its significance in that area of research. It has also been emphasized that the impact of heavily cited articles on scientific research is greater than that of less cited articles (Sharplin and Mabry, 1985; Culnan, 1986). Through citation analysis, researchers can determine the time period during which the major articles in a field were published and how their popularity has evolved over time, and hence if an article is still useful for current research (Pilkington and Meredith, 2009). Although citation analysis has received a lot of criticism, it is regarded as one of the most commonly used techniques for analyzing literature and identifying the most influential author, journal, or work in that particular area of research (Mac Roberts and Mac Roberts 1989, 2010; Vokurka 1996).

Figure 2 demonstrates the top ten influential works published between 2000 and 2015. The most influential article during this period, having received 764 citations, is the work published by Atzori *et al.* (2010). These authors introduced and compared different visions of the IoT paradigm, that is, "Internet oriented," "Things oriented," and "Semantic oriented." In addition, they discussed the enabling technologies and the potential applications of IoT. Another important contribution was by Weber (2010) who devoted to the study of privacy and security challenges related to IoT. This work received 153 citations which reflects the significance of the article in this field. Gubbi *et al.* (2013) provided a Cloud centric vision for IoT. They presented a case study of data analytics based on the "Aneka" cloud platform which is based on interaction of private and public clouds. The article received 136 citations and became the third most influential work of this period. Furthermore, the article by Xu (2011) which has been cited 75 times, increased the awareness of readers in terms of product quality and gave suggestions to explore the roles of service-oriented architecture, RFID, agents, work flow management, and IoT as enablers so that customer value can be improved in new product development. The impact of the work can be identified from the fact that until now 75 scientific articles have been published based on their work. A piece of work by Gunasekaran *et al.* (2009) that received 50 citations becomes the fifth most important article of this time period. The main motive behind their work was to understand the concept of e-procurement in SMEs. They developed a framework for the successful adoption of e-procurement. Table VII shows the numbers of citations received by the influential articles.

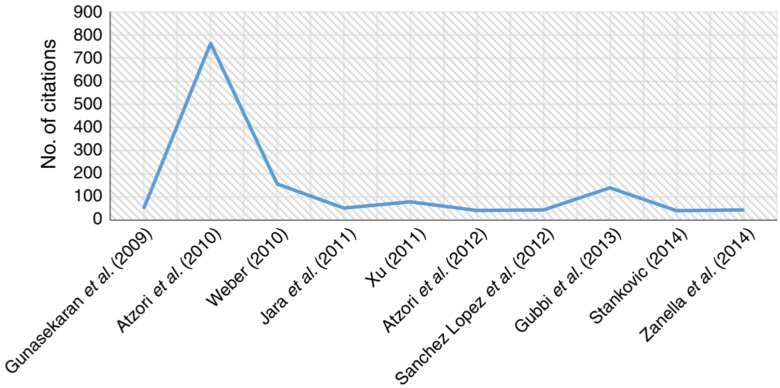

Figure 2.
Frequency distribution of top ten cited articles

Author (year)	Citations
Atzori *et al.* (2010)	764
Weber (2010)	153
Gubbi *et al.* (2013)	136
Xu (2011)	75
Gunasekaran *et al.* (2009)	50
Jara *et al.* (2011)	48
Zanella *et al.* (2014)	40
Sanchez Lopez *et al.* (2012)	40
Atzori *et al.* (2012)	38
Stankovic (2014)	37

Table VII.
Top ten articles based on citations

3.5.2 PageRank analysis. To measure the importance of any article, several methods are available; one is citation analysis which has been discussed above (Ding and Cronin, 2011). Ding *et al.* (2009) emphasized that significance of an article cannot be determined only by measuring the number of citations. Besides popularity, prestige which reflects that how many times an article has been cited by highly cited papers, is an important criteria. Although these measures may be positively correlated in some cases, it is not mandatory that a highly cited paper is also a prestigious paper. Brin and Page (1998) introduced PageRank as a measure for both popularity and prestige, and as an excellent way to prioritize the results of web keyword searches.

Suppose that article A has been cited by papers $T_1, \ldots, T_n$. Define a parameter d as the damping factor, which represents the fraction of random walks that continue to propagate along the citations, and whose value is fixed between 0 and 1. Now, define $C(T_i)$ as the number of times paper T_i has cited other papers. The PageRank of paper A, denoted by $PR(A)$, in a network of N papers is calculated as follows:

$$PR(A) = \frac{(1-d)}{N} + d\left(\frac{PR(T_1)}{C(T_1)} + \ldots + \frac{PR(T_n)}{C(T_n)}\right)$$

It is important to note that if $C(T_i)=0$, then $PR(T_i)$ will be divided to the number of papers instead of $C(T_i)$. The value of parameter d has always been a point of debate. Brin and Page (1998) argued that in the original Google PageRank algorithm, the value of parameter d was fixed at 0.85, while Chen *et al.* (2007) claimed that $d=0.5$ is a more appropriate choice for carrying out PageRank analysis in citation networks.

Table VIII extrapolates the top ten papers using PageRank analysis. When comparing Tables VII and VIII, it is observed that the topmost paper based on citations is Atzori *et al.* (2010). It has still remained on the first position in the list of top ten high-PageRank papers. The second highly cited paper (i.e. Weber, 2010) is not present in the list whereas, the third highly cited paper (Gubbi *et al.*, 2013) came down to the fourth position in Table VIII. Atzori *et al.* (2012), ranked ninth in Table VII, is second in Table VIII.

3.5.3 Co-citation analysis. Co-citation analysis is a way to investigate the relationships between authors, topics, journals, or keywords, thus explaining how these groups are related with each other (Small, 1973; Pilkington and Liston-Heyes, 1999). It can be conducted either on the basis of authors, which helps in manifesting the social structure, or on the basis of publications, which reveals the intellectual structure of research field (Chen *et al.*, 2010). Through co-citation analysis, the major research clusters within a

Author (year)	Page Rank	Citations
Atzori *et al.* (2010)	0.02149	764
Atzori *et al.*(2012)	0.01093	38
Chui *et al.* (2010)	0.00891	67
Gubbi *et al.* (2013)	0.00885	136
Yu *et al.* (2010)	0.00843	45
Gomez and Paradells (2010)	0.00809	119
Kranz *et al.* (2010)	0.00806	89
Katasonov *et al.* (2008)	0.007683	45
Miorandi *et al.* (2012)	0.00768	343
Guinard *et al.* (2010)	0.00763	256

Table VIII.
Top ten articles based on PageRank

particular field and how they evolve and vary across different journals over time can be determined. According to Leydesdorff and Vaughan (2006 cited in Pilkington and Meredith, 2009), the data received through co-citation "can be considered as such linkage data among texts, while cited references are variables attributed to texts [...] one should realize that network data are different from attributes as data. From a network perspective, for example, one may wish to focus on how the network develops structurally over time."

To perform co-citation analysis, a .NET file obtained for 146 articles in BibExcel is opened in Gephi. When the .NET file is opened for the first time, Gephi generates a random map which has no visible pattern. However, different layouts can be created by using various algorithms of Gephi. In this study, we used Force Atlas layout which is highly recommended by developers as it is easy to understand. In these networks, edges attract and nodes repulse each other. It is worth mentioning here that the values of repulsion strength, gravity, speed, node size and other characteristics can be altered manually (Bastian *et al.*, 2009).

On performing co-citation mapping for the first time in Gephi, it was found that 186 articles out of a total of 492 have been co-cited by other papers within this sample. When the .NET file is initially opened, Gephi generates a random map which has no visible pattern. However, different layouts can be created by using various algorithms of Gephi. In this study, we used Force Atlas, a force driven algorithm which is highly recommended by developers as it is easy to understand (Fahimnia *et al.*, 2015). In these networks, edges attract and nodes repulse each other. It is worth mentioning here that the values of repulsion strength, gravity, speed, node size and other characteristics can be altered manually (Bastian *et al.*, 2009). By using this algorithm, the nodes which are strongly connected move to the center of the network whereas, the less connected nodes move out to the boundaries.

The Force Atlas layout of 172 node co-citation map is shown in Figure 3. The co-cited articles are connected with each other while, the poorly connected nodes shift away from the center. Moreover, the nodes which are isolated from rest of the

Figure 3.
Force Atlas layout of 172 nodes (articles)

network, also termed as "outliers," are excluded for the purpose of data clustering, done in the next section. On excluding these outliers we are left with a network having 172 nodes and 862 edges.

3.5.4 Data clustering: identifying research themes in the literature of IoT. Data clustering is a technique to group a similar set of articles together (Radicchi *et al.*, 2004). This can be done by grouping the nodes into clusters such that the edges between the nodes of the same cluster are denser as compared to those of different clusters (Clauset *et al.*, 2004; Leydesdorff, 2011; Radicchi *et al.*, 2004). Blondel *et al.* (2008) argued that the density of links inside communities vs the links between communities can be measured by modularity. The default modularity tool in Gephi is based on Louvain algorithm, and the value of modularity index varies between −1 and +1. Blondel *et al.* (2008) gave the formula for calculating modularity index as follows:

$$Q = \frac{1}{2m}\sum_{ij}\left[A_{ij} - \frac{k_i k_j}{2m}\right]\delta\left(c_i, c_j\right),$$

where A_{ij} represents the weight of the edge between nodes i and j, k_i is the sum of the weights of the edges attached to node i ($k_i = \Sigma_j A_{ij}$), c_i is the community to which vertex i is assigned, $\delta(u, v)$ is equal to 1 if $u = v$ and 0 otherwise, and finally $m = (1/2)\sum_{ij} A_{ij}$.

On applying this algorithm to 172-node network, five major clusters were created. The positioning of and interaction among these clusters is depicted in Figure 4. It can be observed that the thickness of the arcs between the nodes vary from each other, where the thickness reflects the degree frequency for co-occurrence of any two papers in the reference list of other papers. The modularity index for this network was found to be 0.19. This indicates strong inter-relationship between the nodes of each cluster, as well as, between the nodes of different clusters. In view of Hjørland (2013), when two or more papers are often cited together, they probably share similar area of interest. Hence, a detailed analysis of papers belonging to one cluster can help in identifying the research area of that cluster. Since the number of papers in each cluster is high, we

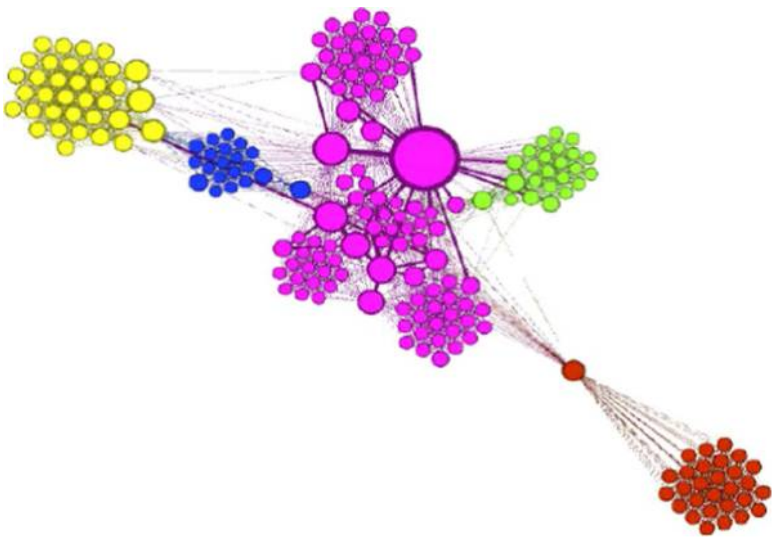

Figure 4.
Structure of five clusters

considered only the top publications of each cluster, on the basis of their co-citation PageRank. Table IX shows the top publications of each cluster.

In order to find out the area of research focus of each cluster, we carefully examined the contents and research areas of the leading papers. We found that research belonging to first cluster is mostly theoretical and conceptual. Researchers in this cluster review the literature and outline current and future challenges (e.g. Atzori *et al.*, 2010, 2012). The aim of the second cluster is to move ahead with well-established concepts and theories and implement them in different fields, including, for instance, IoT in smart cities and hospitals (e.g. Yu *et al.*, 2010). Authors in 3rd cluster are mainly interested in studying the applications of IoT in logistics and supply chain (Luo *et al.*, 2007; Kranz *et al.*, 2010). Researchers belonging to fourth cluster concentrate at designing and planning of IoT whereas, the fifth cluster is devoted to study the security and privacy aspects of IoT (e.g. Katasonov *et al.*, 2008; Zorzi *et al.*, 2010). It can be observed that the first cluster is the most popular one, while there is a scope of future work in clusters 4th and 5th. Therefore, so far literature has mainly focussed on reviewing the literature on IoT and suggesting potential applications in different contexts. Scholars are yet to conduct and report findings on case studies focussing on the adoption of IoT in these contexts, as well as the challenges that may come to the foreground during IoT adoption. Such studies would be important, since it is of crucial importance that information systems (IS) research and practice associates technology innovation with the context within which it is embedded (Avgerou, 2001). Furthermore, there are so far no studies focussing on providing particular frameworks or models on how IoT could be adopted, as well as whether/how IoT is different than other adoption processes of IS, given that the number and type of IoT technology (and devices) is

Cluster 1	*Cluster 2*	*Cluster 3*
Atzori *et al.* (2010)	Yu *et al.* (2010)	Kranz *et al.* (2010)
Atzori *et al.* (2012)	Perera *et al.* (2014)	Luo *et al.* (2007)
Ashton (2009)	Kleinberg (2000)	Mousavi *et al.* (2005)
Chui *et al.* (2010)	Vlacheas *et al.* (2013)	Nissen (2001)
Gubbi *et al.* (2013)	Jin *et al.* (2014)	Lyons *et al.* (2005)
Gomez and Paradells (2010)	Huang *et al.* (2014)	Mangina and Vlachos (2005)
Miorandi *et al.* (2012)	Zhou *et al.* (2011)	Oppong *et al.* (2005)
Guinard *et al.* (2010)	Mathur *et al.* (2010)	Popova and Sharpanskykh (2008)
Bandyopadhyay and Sen (2011)	Newsome *et al.* (2004)	Prisecaru (2008)
Kortuem *et al.* (2010)	Pantelopoulos and Bourbakis (2010)	Papazoglou and Georgakopoulos (2003)
Cluster 4	*Cluster 5*	
Katasonov *et al.* (2008)	Zorzi *et al.* (2010)	
Meyer *et al.* (2009)	Watts and Strogatz (1998)	
Smith (1980)	Stojmenovic and Wen (2014)	
Sarac *et al.* (2010)	Weber (2010)	
Lim *et al.* (2013)	Mohar (1991)	
Melski *et al.* (2008)	Newman (2001	
Zouaghi *et al.* (2010)	Newman (2003)	
Riva (2005)	Mukherjee *et al.* (1994)	
Reaidy *et al.* (2003)	Molloy and Reed (1995)	
Reaidy *et al.* (2006)	Ning *et al.* (2013)	

Table IX. Top ten papers of each cluster: co-citation PageRank measure increasing exponentially every year (Guinard and Vlad, 2009). Finally, since IoT adoption would need to consider the wider socio-organizational context in which it will be embedded, there are yet studies to examine IoT considering the local organizational, but also the national and international context, as well as both the technical/rational decisions and actions involved in the adoption process and the cultural, social, and cognitive forces of such a process.

4. Discussion

In this paper we conducted a bibliometric and network analytics study of the literature related to IoT. This study was triggered because of two facts: first, the IoT literature is growing exponentially, but, however, the literature surrounding IoT is still underdeveloped; and second, IoT has attracted significant attentions from both academics and industry. However, the majority of the literature stems from technology perspective. Research related to the adoption and applications of IoT in business – for instance in particular smart cities, hospitals, and supply chains – are still underdeveloped. In the subsections that follow, we outline our theoretical contribution and the managerial implications of our work.

4.1 Theoretical contributions

The current study provides a bibliometric and network analytics review of the literature on IoT, inspired by Fahimnia *et al.* (2015) and their review of the green supply chain management literature. No matter if we conducted our study in a time span of 16 years, the majority of articles have been published over the last five years. It is also worth mentioning that the top influential studies (as our findings suggest) come from few researchers. Our contribution lies in identifying top contributing authors in the field as well as the key research topics and influential works based on citation analysis and PageRank; and proposing a five-cluster classification of the IoT research themes based on data clustering. Such a clustering is important, we believe, since it enables researchers not only to acknowledge the diversity of research in the field, but also because it provides those areas where more research would need to be conducted. Our study, hence, is differs from reviews such as Atzori *et al.* (2010) or Atzori *et al.* (2012) in that we are not only reporting different visions of IoT and enabling technologies or appropriate policies for the establishment and the management of social relationships through IoT. Research should not only focus on identifying the current and emerging technology solutions for IoT (Katasonov *et al.*, 2008; Gomez and Paradells, 2010), but scholars should attend to the diverse socio-organizational, both local and international, context in which IoT is to be embedded (Avgerou, 2001). The study of Kranz *et al.* (2010) that investigates human-computer interaction as enabled by IoT and related technologies we believe is to the right direction since it shifts the interest from the technology *per se* to how IoT is embedded within human interactions. Yet, there are studies to be conducted on the adoption process and the enablers, drivers, barriers, and models of IoT adoption by organizations and supply chains from both a technological and socio-organizational point of view. Furthermore, there are limited, if any, studies that look into the relationship between IoT adoption and increase of organizational and supply chain performance. Such studies are a necessity, given the recent focus on efficiency and sustainability within the supply chain, and the aim to use technological solutions that enable transparency and visibility at the lowest cost, energy consumption, and environmental footprint (e.g. Malhotra *et al.*, 2013;

Dubey *et al.*, 2016). Finally, paraphrasing the endorsement of scholars (e.g. Holmstrom *et al.*, 2009; Taylor and Taylor, 2009; Ketokivi and Choi, 2014) who suggest the use of alternative lenses to the study of operations management related phenomena, we would like to stress the importance of using alternative theories and mechanisms that look into the wider implications of IoT implementation and adoption. Therefore, based on the findings of this research we identify and propose the following questions:

(1) What are the drivers and barriers of IoT implementation and adoption?

(2) How can we explain IoT implementation and adoption using alternative organizational theories?

(3) How can we measure the impacts of IoT on organizational and supply chain performance?

(4) Can we propose a holistic model that explains the acceptance of IoT applications?

4.2 Managerial implications

Our study has the following managerial implications: first, it enables practitioners to acknowledge the vision and different applications of IoT, as well as the different focus of research clusters; second, suggests that managerial attention should be not only on the selection of technologies, but also on the wider socio-organizational implications of the IoT adoption for organizations and supply chains; and third, it enables managers and decision makers to gain a holistic understanding of the implications of IoT so that they make better decisions with regards to its adoption and the necessary resources that need to be in place to facilitate the transition to the IoT era and the implications of IoT for achieving superior performance.

5. Conclusions, limitations, and future research

The study has reviewed and examined articles published over a period of 16 years (2000-2015) by using bibliometric and network analyses. The main objective of this study was to identify highly cited and co-cited works related to IoT offering future research directions to the IoT research community and implications for managers and decision makers. We have also proposed a five-cluster overview of research themes across IoT. Our results and five-cluster classification of IoT research illustrate the increasing importance of IoT, but on the other hand the studies that acknowledge the applications of IoT for organizations and supply chains and the wider socio-organizational context that needs to be considered; such studies are missing from the literature. Hence, the majority of the highly cited and co-cited works in the field are dominated by conceptualizations and there are few applications of IoT that include case studies, which would provide a more in-depth understanding of how IoT emerges, how it is adopted, and what the advantages and challenges from its use are. Furthermore, our findings highlight the need for alternative theories and lenses to be used in order to study IoT related phenomena. The findings of this study may help scholars in understanding the concept of IoT; the changing research trends in the field of IoT, and those articles that have been influential in shaping research in these years; and intellectual structure of the field.

The paper has the following limitations:

(1) The findings of the review are based on 13 peer reviewed journals with a focus on last 16 years (2000-2015) publications. Certainly, this study may have missed articles published in other peer reviewed journals.

(2) The study adopted bibliometric technique of citation and co-citation analysis for reviewing the literature (Pilkington and Meredith, 2009). There may be other methods to be used for citation and co-citation analysis.

(3) We have used the method of citation analysis but did not focus on the impacts of self-citation. We acknowledge that citation studies tend to exclude self-citation, but today's journal impact factor includes them. It may be that other studies could consider the effect of self-citations and see if current pattern changes by excluding or discounting the self-citation effects.

(4) We have used particular keywords ("IoT") in our searches for abstract, title, and full text. However, the use of other keywords may generate different search results.

(5) We have classified IoT application into four categories. This classification is by no means exhaustive, and other scholars could use in their studies different classifications.

(6) The study has not taken into consideration the technologies and architectural elements of IoT (Gubbi *et al.*, 2013; Borgia, 2014).

Despite the aforementioned limitations, we believe that our current attempt will offer motivation to undertake research to advance IoT and theories to explain IoT related phenomena. We believe that the existing IoT literature can be further enriched through research that examines IoT using behavioral and organizational theories. Furthermore, research on IoT is in nascent stage, and hence we believe that use of research methods such as case studies, ethnography, grounded theory and action research can provide alternative angles to explain the complexity surrounding IoT. Furthermore, studies that shift the focus from purely technological to the socio-organizational implications of IoT adoption, and that suggest holistic models of IoT adoption and implementation would benefit both researchers and managers who would like to further explore IoT. Finally, studies (both case studies and surveys) that explore the drivers and barriers of IoT implementation and adoption as well as its impact on the environment and performance would be strongly needed.

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